Market Demand, Competition for Knowledge Workers, and Impact on Innovation: Evidence from Electric Vehicle Technologies

Abstract

Strategy and innovation scholars have long emphasized the positive role of market demand in driving innovation within a technological domain. This study sheds light on an indirect *negative* spillover effect of market demand on innovation: while increased downstream market demand within a technological domain generally drives increased innovation activities in that domain (i.e., the demand-relevant domain), it may also adversely affect the innovation of firms in adjacent domains. This occurs because the increase in innovation activities within the demand-relevant domain, driven by the downstream market demand, can intensify competition for skilled knowledge workers—a critical innovation resource whose supply is often inelastic in the short term. Empirically, I test these arguments by exploiting an unexpected environmental policy shock—the Zero Emission Vehicle (ZEV) mandate—which led to an exogenous increase in demand for electric vehicle (EV) technologies. Following the ZEV mandate, I find evidence of increased innovation activities in the EV domain by EV firms. However, firms in adjacent (non-EV) domains became 26% less innovative, particularly in their core technological areas, and became 22% less likely to explore new technological areas. This occurred because the affected firms were more likely to lose knowledge workers to EV firms following the ZEV mandate. Notably, affected firms in growing technological domains, such as renewable energy, and smaller, younger firms were more adversely (or at least equally) impacted.

Keywords: market demand; innovation; negative spillover; adjacent technological domains; competition for skilled knowledge workers; rate and direction of innovation; electric vehicle technologies

1. Introduction

Strategy and innovation scholars have long studied the relationship between market demand, innovation activities, and technological change (Schmookler, 1966; Dosi, 1982; Cohen, 2010; Di Stefano, Gambardella, and Verona, 2012). Many studies in the demand-pull literature (e.g., Mowery and Rosenberg, 1979; Adner and Levinthal, 2001; Galasso and Luo, 2021) have examined the direct impact of market demand on innovation, particularly the mechanisms through which an increase in downstream market demand for certain products or technologies can drive increased innovation activities in technological domains that are directly related to those products or technologies (hereafter referred to as demand-relevant domains). Yet, we know surprisingly little about how the same demand may indirectly impact innovation in other technological domains that are not directly related to the products or technologies, potentially through shaping the reallocation of innovation resources across domains.

This research gap exists partly because studies in this literature have paid less attention to an important constraint on innovation: The supply of innovation resources, especially of knowledge workers, is often limited because it can take years to train an additional supply of workers (Goolsbee, 1998; Stephan, 2015). This paper addresses this gap by proposing that, while an increase in downstream market demand can directly drive *positive* innovation progress in a demand-relevant domain, it may also create indirect *negative* spillover effects on the innovation progress of firms in *adjacent technological domains*.[1] This occurs because the increase in innovation activities within the demand-relevant domain can intensify competition for knowledge workers (e.g., inventors),[2] a critical innovation resource whose supply is often inelastic in the short term.

A clearer understanding of this dynamic can offer a more comprehensive perspective on how changes in market demand within one domain both directly and indirectly impact innovation in different domains. Such insights not only advance our scholarly understanding of how market demand shapes the broader technological

[1] I define a "demand-relevant domain" as a technological domain that directly experiences increased demand. I define "adjacent technological domains" (or "adjacent domains," interchangeably) as other technological domains that are technologically related to the demand-relevant domain; accordingly, knowledge workers employed by firms in adjacent domains will likely have knowledge related to demand-relevant domain. Consequently, firms in adjacent domains may be at risk of losing their knowledge workers to firms in the demand-relevant domain.

[2] In this study, I use the terms "knowledge worker" and "inventor" interchangeably.

landscape (Schmookler, 1966; Cohen, 2010; Di Stefano, Gambardella and Verona, 2012), but also prove strategically important for firms and public organizations interested in understanding the trajectory of technological evolution. For example, while the rise of artificial intelligence (AI) has garnered immense attention over the past decade, there are concerns that its growth has resulted in unintended consequences for firms in other critical domains and sectors, such as semiconductors, aerospace and defense, oil and gas, automotives, and manufacturing. This has occurred because the need to develop AI siphons innovation resources, particularly knowledge workers, from these domains (*Forbes*, 2015; *Wall Street Journal*, 2015a; McKinsey & Company, 2022; *New York Times*, 2023; *ISG*, 2025). Similarly, in its effort to build autonomous vehicles, Apple has poached scientists and engineers from automakers, tech companies, and battery manufacturers; the loss of R&D workers has forced these companies to abandon key projects or even to go bankrupt (*Guardian*, 2015; *Reuters*, 2015; *Wall Street Journal*, 2015b). Additionally, the burgeoning crypto and Web3 sectors have drawn many highly skilled knowledge workers from firms in industries such as finance and technology (Zycrypto, 2018; *Fortune*, 2022; *New York Times*, 2022). More recently, the government's increased support for COVID research drained innovation resources—especially scientific and innovation talent—from other areas of disease research. This indirect negative impact has been particularly pronounced for some already-neglected tropical diseases that have afflicted hundreds of millions among the low-income population for decades (The Conversation, 2022; Nature India, 2022).

This study investigates how changes in downstream market demand within a technological domain may affect the rate and direction of innovation among firms in adjacent domains by shaping the competitive landscape for knowledge workers. By integrating theoretical perspectives on demand-pull innovation, resource allocation, and mobility of knowledge workers, I posit that, following an increase in downstream market demand within a technological domain (i.e., a demand-relevant domain), firms in adjacent domains (hereafter referred to as affected firms) may become less innovative because they are more likely to lose knowledge

workers to firms in the demand-relevant domain.[3] In particular, the affected firms not only become less innovative in their core technological areas but also become less likely to explore new technological areas.[4, 5]

Using observational data to test these arguments presents several challenges. First, other factors—such as the emergence of new technological opportunities, other market conditions, and labor market frictions—may simultaneously impact both market demand and innovation progress across firms and domains. Furthermore, knowledge workers' decisions to move between firms can endogenously affect innovation progress and future market-demand conditions. Addressing these concerns ideally requires an experiment that randomly assigns certain technological domains to experience an increase in downstream market demand. This would make it possible to observe whether firms in adjacent technological domains become less innovative, and whether this is driven by their loss of knowledge workers to firms in the demand-relevant domain. To approach this ideal setting, I exploit the unexpected Zero Emission Vehicle (ZEV) mandate in September 1990 as an exogenous shock that resulted in an unanticipated increase in demand for electric vehicle (EV) technologies.

The ZEV mandate was adopted by the California Air Resources Board (CARB) in 1990. Importantly, the mandate was adopted not because of ex ante progress in EV technologies but because of CARB's efforts to address California's severe air pollution. As the number of automobiles in California surged in the 1980s, CARB found that the prior tailpipe emission standards were no longer adequate for controlling air pollution. Hoping to improve the air quality, CARB adopted the ZEV mandate, which required the sale of electric vehicles for the first time in history. Consequently, this mandate led to unprecedented, unanticipated demand for EV technologies such as energy storage and conversion materials, traction motor technologies, and lightweight materials (Calef and Goble, 2007; Collantes and Sperling, 2008). Thus, the ZEV mandate is well suited for studying my research question, particularly because firms in technological domains adjacent to the EV

[3] In this study, I refer to firms in domains adjacent to the demand-relevant domain as "affected firms." Hereafter, I use the terms "firms in adjacent domains," "adjacent firms," and "affected firms" interchangeably.
[4] I define a firm's "core technological areas" as those technological areas in which the firm specializes, and define "new technological areas" as those that are new to the firm. Empirically, I measure a firm's core technological areas as the CPC subclasses in which it has patented most frequently, and new technological areas as the CPC subclasses that are new to the firm.
[5] I use the terms "core technological *areas*" and "new technological *areas*" to distinguish them from technological *domains*.

domain—especially firms adversely affected by the mandate—were unlikely to have anticipated or supported its adoption. Furthermore, many policy studies have documented that even the automotive industry, which was targeted by this mandate and had neglected EV technologies throughout the 1970s and 1980s, strongly opposed it and invested in EV technologies mainly in response to the mandate's sales requirements (e.g., Calef and Goble, 2007).

Using a difference-in-differences methodology, I find that the increased demand for EV technologies following the ZEV mandate negatively affected the rate and direction of innovation by firms in technological domains adjacent to the EV domain. After the ZEV mandate, EV firms increased their innovation activities in the EV domain. However, firms in adjacent technological domains (i.e., affected firms)—relative to comparable control firms that were less impacted by the ZEV mandate—became 26% less innovative, particularly in their core technological areas, and 22% less likely to explore new technological areas. This occurred because the affected firms were 670% more likely to lose inventors to EV firms following the ZEV mandate. In particular, the adverse effects were greater—or at least equal—for affected firms in growing technological domains (such as renewable energy) and for smaller, younger firms. Further analyses suggest that the main effects were driven by a subset of affected firms that originally employed inventors with knowledge relevant to EV innovations; these inventors were, on average, more likely to move to EV firms following the ZEV mandate.

This study makes several important contributions. First, it contributes to research on the determinants of the rate and direction of innovation (Schmookler, 1966; Cohen, 2010; Di Stefano, Gambardella, and Verona, 2012; Teodoridis, 2018; Furman and Teodoridis, 2020). In particular, research in the demand-pull literature has made extensive progress in understanding how changes in downstream market demand for certain products or technologies shape innovation in technological domains directly related to those products or technologies (Mowery and Rosenberg, 1979; Adner and Levinthal, 2001; Acemoglu and Linn, 2004; Fabrizio and Thomas, 2012; Byrski, Gaessler, and Higgins, 2021; Galasso and Luo, 2021). However, while most research has focused on the direct impact of market demand on innovation, we know significantly less about how the same demand may affect innovation progress in other technological domains by shaping the competitive landscape for innovation resources. My findings complement existing research by shedding light on the potential negative

spillover effects of such demand changes, which affect firms in other technological domains through competition for knowledge workers. These findings contribute to a more holistic understanding of how changes in market demand shape the evolution of different domains and by extension, the broader technological landscape.

Second, by bridging the demand-pull and worker-mobility literatures, this study offers a more complete understanding of the interactive relationship between innovation activities and worker mobility. It highlights how a focal firm can be affected by market and technological changes, especially by changes in seemingly unrelated industries or technological domains; these changes can lead to unexpected inventor loss that ultimately undermines the firm's technological capabilities. Understanding these dynamics is particularly important given the emergence of fast-growing, R&D-intensive industries that have accelerated market and technological changes, potentially intensifying the competition for knowledge workers. Furthermore, given the resource-intensive nature of most innovation activities and the inelastic supply of high-skilled knowledge workers, our understanding of the connection between worker mobility and innovation should extend beyond a mere focus on the hiring firms' benefits from employing skilled workers (Singh and Agrawal, 2011; Ganco, Miller, and Toh, 2020; Dimmock, Huang, and Weisbenner, 2022). In R&D-intensive industries such as artificial intelligence and electric and autonomous vehicles, due to the inelastic supply of high-skilled workers, one firm's gain in knowledge workers is often another firm's loss (*Forbes*, 2015; *New York Times*, 2023; *ISG*, 2025). This study sheds light on how growth in one technological domain might shape the competitive landscape for high-skilled knowledge workers and might result in indirect consequences for firms in other domains.

This study also contributes to the literature on firms' reallocation of innovation resources. While existing research has extensively explored how firms reallocate resources to capitalize on new innovation opportunities (e.g., Helfat and Eisenhardt, 2004; Levinthal and Wu, 2022; Karim, Lee, and Hoehn-Weiss, 2023; Kim, Guler, and Karim, 2024), the findings suggest that as new innovation opportunities arise and as innovation activities intensify within the domain, some firms in other domains may lose innovation resources. Furthermore, this loss of innovation resources can, in turn, hinder these firms' ability to diversify into new technological areas.

The findings have far-reaching policy and managerial implications. First, this study highlights the adverse effects of an innovation policy on firms. Policymakers have frequently adopted various demand-side policies, such as tax subsidies and procurement, to stimulate innovation in certain technological domains. However, my findings suggest that, when designing innovation policies, policymakers should think more broadly about the potential indirect spillover effects of such policies because their increased support in one technological domain may indirectly erode the innovation progress of firms in other domains. For example, we should have expected policymakers who adopted the ZEV mandate to also care about the innovation progress of firms in other emerging renewable energy domains.[6] However, I find that firms in renewable energy domains were adversely affected because they lost inventors to EV firms. At the minimum, policymakers should account for these negative spillover effects when evaluating the overall efficiency and effectiveness of innovation policies.

The findings also offer valuable insights for managerial practices. The results suggest that market and technological changes in seemingly unrelated areas can impact firms' resources and capabilities through competition for knowledge workers. Therefore, firms should think more broadly about their boundaries and underlying technical capabilities; failing to do so may place them at risk of losing knowledge workers and other valuable innovation resources. Specifically, firms should recognize the threat of losing knowledge workers to other firms that may not be direct competitors in the same product market but may operate in a related technological domain. Understanding this is particularly crucial given the recent and rapid emergence of R&D-intensive industries, which has accelerated the pace of technological change and introduced new challenges for firms.

2. Conceptual Framework

2.1. Market Demand, Innovation, and Knowledge Workers

The role of market demand in driving innovation has been an important topic of scholarly discussion for decades (Schmookler, 1966; Mowery and Rosenberg, 1979; Dosi, 1982; Rosenberg and Nathan, 1982; Cohen,

[6] I provide evidence supporting this in **Appendix Figure A8**.

2010; Galasso and Luo, 2021). This "demand-pull" literature considers the importance of demand characteristics and market features in shaping innovation progress. More recent work in this literature has examined the roles of market size (Acemoglu and Linn, 2004), consumer demand heterogeneity (Adner and Levinthal, 2001), and customers and lead-user demand (von Hippel, 1986; Franke and Shah, 2003) on innovation progress. Overall, there is broad consensus that (anticipated) market demand plays a direct and critical role in driving the rate of innovation progress in a focal technological domain (Mowery and Rosenberg, 1979).

However, most studies in this literature have paid much less attention to an important constraint on innovation: The supply of innovation resources, especially of knowledge workers, is often inelastic, at least in the short term. This lack of attention carries significant implications because most innovation activities are highly resource-intensive and knowledge workers are a critical, yet often scarce, resource for innovation (Goolsbee, 1998; Cohen, 2010; Stephan, 2015). In fact, studies of scientific human capital have suggested that the supply of new innovation labor often cannot adjust immediately to changes in labor demand; this is especially true for high-skill workers as it can take four to five years to train additional PhD scientists and engineers to meet increased demand (Goolsbee, 1998; Stephan, 2015; Ahmed, Wahed, and Thompson, 2023).

Relatedly, the literature on spinoffs also suggests that incumbent firms are sources of startups, which, in turn, can contribute to increased mobility of knowledge workers, particularly during periods of market and technological change (e.g., Klepper and Sleeper, 2005; Cheyre, Klepper, and Veloso, 2015). For example, Cheyre, Klepper, and Veloso (2015) find that, in the semiconductor industry, the entry of spinoffs resulted in higher mobility of inventors in Silicon Valley, even before the industry was clustered there. Consequently, spinoffs can further contribute to a tightened labor market by intensifying competition for knowledge workers.

Therefore, given the inelastic supply of new innovation labor, we would expect that growth in innovation activities in one technological domain might lead to increased demand—and increased competition—for knowledge workers with relevant expertise.

2.2. Market Demand Changes, Competition for Knowledge Workers, and Innovation Outcomes Among Firms in Adjacent Technological Domains

I argue that an increase in downstream market demand within a technological domain can negatively affect the rate and direction of innovation by firms in adjacent domains. This occurs because firms in the demand-relevant domains, which have increased innovation activities driven by downstream market demand, may compete away knowledge workers from firms in adjacent domains.

Following the increase in downstream market demand, firms in the demand-relevant domain will have greater incentives to develop more innovations within that domain (Schmookler, 1966; Mowery and Rosenberg, 1979; Acemoglu and Linn, 2004; Galasso and Luo, 2021); this, in turn, likely increases their demand for knowledge workers. When firms have greater demand for certain skills or attributes, they are more likely to offer promotions and higher payoffs, such as increased salaries or resources, to attract knowledge workers with relevant skills or attributes, especially when the demand for workers is not immediately matched by an increase in worker supply (Kokkodis and Ipeirotis, 2021; Gormley et al., 2023; Roach and Sauermann, 2023; Bloom et al., 2024). For example, the recent growth of artificial intelligence (AI) has led to increased demand for skills related to AI technologies, which has outpaced the supply of AI talent (Ahmed, Wahed, and Thompson, 2023). As a result, firms looking to invest in AI offer increasingly higher salaries and innovation resources to attract scientists and engineers with relevant or complementary expertise (Alekseeva et al. 2021; Bessen, Denk, and Meng, 2022). Thus, as market demand and corresponding innovation activities increase, firms in the demand-relevant domain will have increased incentive to compete away knowledge workers from firms in adjacent domains, since these knowledge workers are more likely to possess knowledge relevant to innovation in the demand-relevant domain than are knowledge workers from non-adjacent domains.

Also, knowledge workers will have greater incentives to leave their current employment in adjacent domains to join firms in the demand-relevant domain. Studies suggest that knowledge workers are more likely to change employers when the value of their human capital increases (Palomeras and Melero, 2010; Byun, Raffiee, and Ganco, 2019). This occurs because mobility can lead to opportunities for promotions and increased payoffs such as salaries and access to innovation resources (Bidwell, 2011, 2013; Byun, Raffiee, and Ganco,

2019).[7] Although workers' employers may attempt to retain them, we expect to observe more mobility on average, particularly as workers encounter more external opportunities when the increased demand for their knowledge leads to an increase in the value of their human capital.[8]

Furthermore, I argue that the affected firms will experience negative consequences in their rate and direction of innovation after losing knowledge workers to firms in the demand-relevant domain. Knowledge workers are critical to a firm's core technological capabilities and to its ability to diversify into new technological areas (Toh, 2014; Ganco, Miller, and Toh, 2020; Vakili and Kaplan, 2021). Particularly, they contribute to a firm's innovation activities not only through their direct knowledge inputs but also through their indirect positive influence on their colleagues' productivity, which occurs through various channels including collaboration and knowledge spillover (Groysberg and Lee, 2008; Azoulay, Graff Zivin, and Wang, 2010; Borjas and Doran, 2015; Jaravel, Petkova, and Bell, 2018). Therefore, after losing knowledge workers to firms in the demand-relevant domain, the affected firms will become less innovative, both in their core technological areas and in their exploration of new technological areas.

To summarize, following an increase in downstream market demand within a technological domain, firms in adjacent technological domains will become less innovative in their core technological areas and become less likely to explore new technological areas because they will lose knowledge workers to firms in the demand-relevant domains.

3. Research Setting

3.1. Identification Challenges

[7] For example, Bidwell (2011) finds that workers hired externally received 18% higher salaries than those hired internally. This suggests that workers whose human capital becomes more valuable would be better off switching to a new employer rather than staying with their current employer, all else being equal.

[8] For example, consider an inventor whose knowledge and skills are applicable to battery material R&D and who is employed by a chemical company. Before any changes in market-demand conditions, the demand for these inventors was in a certain equilibrium. However, after an increase in market demand for EV technologies, the value of the inventor's knowledge to an EV company increases relative to their value to the current employer. As a result, the inventor will, on average, be more likely to move to the EV employer because the increased market demand increases the inventor's value and outside opportunities.

There are several identification challenges when using observational data to study how changes in market demand within one technological domain affect the innovation progress and loss of knowledge workers among firms in adjacent domains. First, market demand, innovation, and the movement of knowledge workers may be simultaneously affected by other factors, including the emergence of new technological opportunities, market conditions, and labor market frictions. Additionally, knowledge workers' decisions to move between firms may endogenously affect firms' innovation progress that, in turn, could influence future market demand conditions. While these factors are less likely to cause serious endogeneity concerns—given that it is relatively unlikely for them to impact one domain positively while simultaneously impacting other domains negatively—this possibility cannot be ruled out entirely in a correlational analysis.

In an ideal experiment, I would start with different technological domains and randomly allocate an increase in downstream market demand to some domains (i.e., these would become demand-relevant domains). Subsequently, I would examine whether firms in domains adjacent to the demand-relevant domains—compared with firms not in adjacent domains—become less innovative due to the loss of knowledge workers to firms in demand-relevant domains.

3.2. The Zero Emission Vehicle (ZEV) Mandate

To approach this ideal setting, I exploit the unexpected Zero Emission Vehicle mandate in September 1990 as an exogenous shock that resulted in an unanticipated increased demand for electric vehicle (EV) technologies. Importantly, this mandate was adopted not because of major ex ante progress in EV technologies but because of the government's efforts to mitigate California's increasingly worsening air pollution (Calef and Goble, 2007; Collantes and Sperling, 2008; Vergis and Mehta, 2012).

3.2.1. Background

California has been recognized as a leader in environmental policy. As the most populous state, it has had the worst air quality in the United States. In response, it has led the country in adopting aggressive emission reduction policies, especially those targeting the transportation sector, the major source of air pollution in the

state. Because of California's severe air pollution problems and its pioneering efforts in combating air pollution beginning in the late 1950s, federal law has enabled the state to enact vehicle emission standards independent from, and more stringent than, federal standards (National Research Council, 2006). Many other states have followed and adopted California's emission standards instead of federal standards (Vogel, 1997; Shulock et al., 2011).

However, despite stringent emission-reduction legislation and advancements in emission-control technologies (e.g., catalytic converters, fuel injection, variable valve controls), progress in improving air quality remained inadequate in California. Growth in population—alongside a rise in the number of automobiles and the popularity of sport utility vehicles and light trucks (which produce more emissions than passenger cars)—largely offset the air quality improvements brought by emission-control technologies. As a result, air pollution worsened in the 1980s, and California dominated other states in various air pollution indexes, such as the number of areas with the highest ozone levels and the most frequent violations of federal standards (Calef and Goble, 2007). This air pollution problem put California at risk of losing federal funding and support such as funds for transportation infrastructure unless it demonstrated progress toward improving air quality (Collantes and Sperling, 2008).

3.2.2. The ZEV Mandate and Demand for Electric Vehicle Technologies

In September 1990, the California Air Resources Board was convinced that existing emission regulations were insufficient to address the worsening air pollution and adopted the ZEV mandate—arguably the most daring air quality regulation to date. Unlike previous policies, this mandate was the first to require the sale of zero-emission vehicles, which at the time referred mainly to electric vehicles[9]—an entirely different technology from gasoline vehicles. The mandate could not be met with gasoline-powered cars, even with those equipped with the most advanced emission-control technology available. Specifically, the mandate required that, by 1998, 2% of new vehicles sold in California must be zero-emission vehicles. Auto manufacturers with sales of 35,000 or

[9] In this study, "electric vehicle" is used as an umbrella term encompassing various broadly defined electric vehicles, such as battery electric vehicles, hybrid electric vehicles, and fuel cell electric vehicles.

more vehicles per year in the state were subject to the mandate; these included Chrysler, Ford, GM, Honda, Mazda, Nissan, and Toyota. The required percentage of ZEV sales would increase to 5% in 2001 and 10% in 2003, with a $5,000 fine imposed for each vehicle short of the requirement.[10]

By mandating the sale of electric vehicles, the ZEV mandate created an unanticipated and unprecedented need to develop EV technologies, which had been dormant for decades. In fact, immediately after its adoption, automakers strongly opposed the mandate, arguing that existing EV technology was underdeveloped and that producing EVs with current technologies would result in a market fiasco. Nevertheless, the industry had no choice but to comply with the mandate and to invest in the technology. For example, in January 1991, the Big Three automakers—Chrysler, Ford, and GM—pooled resources with the Department of Energy and the electric utility industry to launch the U.S. Advanced Battery Consortium, whose mission was to accelerate progress in developing battery technologies, one of the critical bottlenecks for electric vehicles. Automakers not directly mandated at the time—such as BMW and Volkswagen—were also concerned about being targeted in the future and also increased their investments in EV technologies.

The ZEV mandate is therefore well suited for studying how changes in market demand within one technological domain (i.e., the EV domain) affect innovation progress and inventor loss among firms in adjacent domains. It is unlikely that firms in domains adjacent to the EV domain—particularly those adversely affected by the ZEV mandate—would have anticipated, let alone supported, the adoption of the mandate. Indeed, policy studies have suggested that even many automobile companies, which had largely neglected research on EV technologies and advanced batteries since the 1970s, did not support the ZEV mandate,[11] and they invested in EV technologies during the 1990s mainly as a result of the mandate (Calef and Goble, 2007; Collantes and Sperling, 2008; Vergis and Mehta, 2012). While the ZEV mandate is not strictly an example of market demand driven by end-consumer needs, I argue that, by imposing specific sales requirements for electric vehicles, it has had similar effects in driving firms' incentives to invest in EV technologies.

[10] I provide additional details on the institutional and historical background and impact of this mandate in **Appendix C**.
[11] For example, automotive companies—including GM, DaimlerChrysler, and Isuzu Motors—filed lawsuits in the early 2000s to overturn the ZEV mandate (Calef and Goble, 2007; O'Dell, 2002). See **Appendix C** for further details.

4. Data and Empirical Strategy

4.1. Data and Sample Construction

I examine whether, following the ZEV mandate, firms in adjacent domains (i.e., affected firms) became less innovative because they were more likely to lose inventors to EV firms than firms not in adjacent domains (i.e., control firms). I measure firms' innovation progress and inventor loss using USPTO patent data from PatentsView, which offers disambiguated assignee and inventor information.[12] I date patents by application year (rather than by grant year).

I started by identifying a list of EV firms active in developing EV technologies after the ZEV mandate. To do so, I collect a list of CARB's policy reports and studies on the ZEV mandate.[13] These authoritative reports and studies document progress in EV technologies and identify the companies that made major advancements in these technologies during the 1990s. These include automakers, especially those mandated to sell electric vehicles (e.g., General Motors, Ford, Honda, Toyota) as well as suppliers of EV components such as batteries for electric vehicles (e.g., Matsushita/Panasonic, Sony, Ovonic Battery Company, Johnson Controls), charging technology (e.g., Aerovironment, Norvik), electric motors (e.g., AC Propulsion), and fuel cell electric vehicles (e.g., Ballard Power Systems). By cross-matching firms in the patent database with firms mentioned in these reports, I identified 111 firms that were active in EV-related technologies during the 1990s.

To identify patents related to EV technologies, I take advantage of the Cooperative Patent Classification (CPC) scheme. I identify sixteen EV patent subclasses under Y02T (Climate Change Mitigation Technologies Related to Transportation), and the three energy storage subclasses with application for EV technologies, which are under Y02E60 (Technologies with a Potential or Indirect Contribution to GHG Emissions Mitigation). The three subclasses include Y02E60/10 (Energy Storage Using Batteries), Y02E60/13

[12] See https://patentsview.org/disambiguation. PatentsView's disambiguation algorithm has been demonstrated to have high accuracy and has been frequently used by recent studies (e.g., Kang and Lee, 2022; Ballesteros, 2024). I also ensured the quality of the disambiguation with the help of two research assistants who manually checked and further cleaned the assignee names in my sample.

[13] These reports and studies were produced either directly by the CARB or by research institutions, such as the Institute of Transportation Studies at the University of California, Davis, that were highly involved with CARB's policy adoption and design process, See **Appendix B1** for a list of these documents.

(Energy Storage Using Capacitors), and Y02E60/50 (Fuel Cells).[14] These nineteen subclasses constitute the EV domain and correspond to 17,237 patent filings related to EV technologies in the years 1981–2000.[15] This sample period spans ten years before and ten years after the ZEV mandate.

After locating the EV domain, I identify adjacent technological domains, specifically other CPC subclasses that overlap in technological knowledge with the EV subclasses. A patent is usually assigned to multiple CPC subclasses from which it has drawn knowledge. For example, an EV patent titled "Battery-Powered Electric Vehicle D.C. Motor Control" has been assigned to multiple CPC subclasses, including the EV subclasses above and to other subclasses such as H02P7/281, which is related to electric DC motors. While H02P7/281 is not an EV subclass per se, it overlaps technologically with EV subclasses. This suggests that inventors in this subclass, who possessed knowledge of electric DC motors, would likely have had relevant expertise for developing EV innovations. Consequently, such inventors were at risk of changing employers after the ZEV mandate. I restrict the subclasses to those with at least three patents overlapping with the EV subclasses before the ZEV mandate to ensure they are sufficiently adjacent to the EV subclasses.[16, 17] Thus, I use CPC classification to identify a total of 797 other patent subclasses that—though not EV subclasses per se—were technologically relevant to the EV subclasses for the years 1986–1990 (the five years before the ZEV mandate). I define these subclasses as *adjacent technological domains* to the EV domain.

After constructing the adjacent technological domains, I then track firms with more than 10% of their patents in these adjacent subclasses within the five years before the ZEV mandate (i.e., 1986–1990),[18] but that were not identified as EV firms in the policy reports above. These are the "affected firms" that, to various degrees, employed inventors who might have had relevant knowledge for EV innovations and thus were at risk

[14] These patent subclasses are considered directly related to EV technology because energy storage, such as batteries and fuel cells, has been—and continues to be—a critical bottleneck for electric vehicles. Because of this, after the ZEV mandate the Big Three automakers—Chrysler, Ford, and GM—pooled significant innovation resources to form the U.S. Advanced Battery Consortium (USABC); they, along with other EV companies and EV battery suppliers such as Sony corporation, also filed a significant number of patents in these subclasses. See **Appendix C** for more details.
[15] I provide a list of the nineteen subclasses in **Appendix Table B1**.
[16] Main results remain robust to other cutoffs.
[17] I provide a representative list of these subclasses in **Appendix Table B2**.
[18] I choose a 10% threshold to ensure that these firms were sufficiently "exposed" to the EV demand shock. In **Appendix Figure A4**, I show that the results remain robust to other cutoffs, such as 7.5%, 12.5%, 15%, and 20%.

of losing inventors to EV firms after the ZEV mandate.[19] In these adjacent domains, I identify 953 firms that I refer to as "affected firms" or "adjacent firms" hereafter. To better understand these firms, I plot their North American Industry Classification System (NAICS) distribution in **Appendix Figure B1,**[20] which shows that about 30% of the affected firms were in the Chemical Manufacturing industry; others were in Computer and Electronic Product Manufacturing (15%), Plastics and Rubber Products Manufacturing (15%), Machinery Manufacturing (13%), and Nonmetallic Mineral Product Manufacturing (6%), or other industries.

After identifying these affected firms, I construct a list of control firms. In an ideal empirical design, other firms—comparable to the affected firms in terms of technological knowledge, but less impacted by the ZEV mandate than affected firms—would be identified. To approach this, I collect a list of four-digit CPC subclasses in which the affected firms had patented during 1986–1990, but excluded the adjacent subclasses mentioned above. Next, I identify other firms that patented in these four-digit subclasses (but not in the adjacent subclasses) during 1986–1990 and define these as the control firms. This results in 4,181 control firms comparable to the affected firms but farther from the EV domain and therefore relatively less affected by the increase in demand for EV technologies. I restrict both the affected and control firms to those with at least three patents during 1986–1990 to more accurately characterize each firm's technological domain.[21]

4.2. Empirical Strategy

4.2.1. Baseline Analysis: Increase in EV Innovation Activities by EV Firms Following the ZEV Mandate

In this section, I conduct a baseline analysis using the EV firms to confirm that the ZEV mandate led them to increase their EV innovation activities. While it may not be surprising to observe that increased demand for EV technologies resulted in greater EV innovation, confirming this effect before the main analysis ensures

[19] **Table 7** and **Figure A2** provide direct evidence that these affected firms were negatively impacted by the ZEV mandate precisely because they had hired inventors with relevant knowledge for EV innovations; these inventors had stronger incentives to leave the adjacent firms and join EV firms after the ZEV mandate (see **Section 6.2** for more details).
[20] As patent data does not include information on the industry of assignee firms, I use the CPC-to-NAICS concordance constructed by Goldschlag, Lybbert, and Zolas (2016) to identify the main NAICS industry code for the firms in my sample.
[21] The results remain robust to other cutoffs.

alignment with my theoretical framework. Formally, I estimate a difference-in-differences OLS model with panel data at the firm-year level for the years 1981–2000.

$$EVPatentCount_{jt} = \beta\left(EV\ firm_j \times AfterZEV_t\right) + Age_{jt} + \gamma_j + \delta_t + \varepsilon_{jt} \quad (1)$$

where $EV\ firm_j$ is a dummy variable equal to 1 for the EV firms identified in CARB's policy reports, and 0 for the control firms. For this analysis, I use the same set of control firms as in the main analysis. $AfterZEV_t$ is an indicator variable equal to 1 for years 1991–2000, namely after the ZEV mandate, and 0 otherwise. Age_{it} controls for firm j's age in year t. The term γ_j captures firm fixed effects, and γ_t captures year fixed effects. The dependent variable $EVPatentCount_{jt}$ captures the number of EV patents produced by firm j in year t (dated by application year). I cluster standard errors at the firm level for all regressions. I am interested in interpreting the coefficient β, where a positive estimated value indicates that the EV firms produced more EV patents following the ZEV mandate.

4.2.2. Main Analysis: Consequences of the ZEV Mandate for Firms in Adjacent Technological Domains

After confirming the increase in EV innovation activities by EV firms, I conduct the main analysis to examine whether, following the ZEV mandate, firms in adjacent domains (i.e., affected firms) became less innovative because they lost inventors to EV firms. Formally, I estimate a difference-in-differences OLS model with panel data at the firm-year level for the years 1981–2000.

$$DV_{it} = \beta(Affected\ firm_i \times AfterZEV_t) + Age_{it} + \gamma_i + \delta_t + \varepsilon_{it} \quad (2)$$

where $Affected\ firm_i$ is a dummy variable equal to 1 for firms in the adjacent technological domains (of the EV domain), and 0 for the control firms. $AfterZEV_t$ is an indicator variable equal to 1 for years 1991–2000,

namely after the ZEV mandate, and 0 otherwise. Age_{it} controls for firm i's age in year t. The term γ_i captures firm fixed effects, and γ_t captures year fixed effects.

I exploit two categories of dependent variables DV_{it}: (1) $Innovation_{it}$ and (2) $Net\ inventor\ loss_{it}$. First, $Innovation_{it}$ captures firm i's rate and direction of innovation in year t using various measures. For $Patentcount_{it}$, I count the number of patents granted to firm i in year t, dated by application year. I also count the number of patents in firm i's "core technological areas" (defined as the firm's three most frequently patented four-digit CPC subclasses before the ZEV mandate), and in its "peripheral technological areas" (measured as the firm's patents that are not in its core technological areas). For $NewTechArea_{it}$, I measure firm i's propensity to explore new technological areas in year t by counting the four-digit CPC subclasses that were new to firm i and in which it filed patents in year t. A CPC subclass is defined as new to firm i if the firm did not apply for patents in that subclass within the previous five years. To measure $AvgPatentOriginality_{jt}$, I capture the breadth of technological knowledge drawn upon by firm i in year t (Trajtenberg, Henderson, and Jaffe, 1997). For each of firm i's patents in year t, I calculate the diversity of four-digit CPC subclasses cited by the focal patent; a higher value suggests greater originality because the patent draws from a broader array of technologies. I then aggregate these values at the firm-year level to calculate the average originality per patent for firm i in year t.

Second, $Net\ inventor\ loss_{it}$ captures firm i's number of net inventors lost in year t. I construct $Net\ inventor\ loss_{it}$ following prior literature (Marx, Strumsky, and Fleming, 2009; Kong, 2020; Melero, Palomeras, and Wehrheim, 2020). Specifically, I track inventor mobility by identifying years when inventors applied for patents with employers different from those listed in their previous patent applications. I identify the employers of inventors by using ownership reassignment information from the USPTO Patent Assignment Dataset (Marco et al., 2015).[22] For each firm, I assume an inventor's move-in year to be the year when the

[22] For all applications filed before September 16, 2012, USPTO patents had to be issued to human inventors. Because inventor-employees are typically under contractual obligations to transfer ownership of a patent to their employers, it was necessary to file a change of title from the inventor to the employer with the USPTO (Marco et al., 2015). Therefore, this dataset allows me to identify a firm's inventor-employees.

inventor-employee filed their first patent for that firm, and the move-out year to be the year when they filed their first patent for a subsequent firm.[23] Lastly, I aggregate the number of mobile inventors at the firm-year level and calculate net inventor loss as the count of inventors leaving firm i minus the count of inventors joining firm i in year t.

I am interested in interpreting the coefficient β. For $Innovation_{it}$, a negative estimated value of β indicates that affected firms, relative to control firms, became less innovative after the increase in demand for EV technologies. For $Net\ inventor\ loss_{it}$, a positive estimated value of β indicates that affected firms were more likely to lose inventors after the increase in demand for EV technologies, relative to the control firms.

I present the descriptive statistics for all variables in **Table 1**.

5. Results

5.1. Increased EV Innovation Activities by EV Firms

I start by showing that, following the ZEV mandate, EV firms increased their innovation activities in the EV domain. **Table 2** suggests that the EV firms, on average, produced 3.9 more EV patents after the ZEV mandate, relative to the control firms. This amounts to a 302% increase in the number of EV patents.[24]

In **Figure 1**, I examine the timing of this effect to ensure that increased EV patent count by EV firms is driven by the increase in demand for EV technologies following the 1990 ZEV mandate. In **Figure 1(a)**, I use raw data to plot the yearly average number of EV patents by EV and control firms. In **Figure 1(b)**, I repeat Equation (1) but replace $AfterZEV_t$ with a series of year-specific dummy variables; I plot the estimated coefficients of the interaction between the EV firm dummy and these year-specific dummies. The graphs show that the difference between the EV and control firms was small and stable before the 1990 ZEV mandate. Thereafter, EV firms produced more EV patents relative to the control firms, as evidenced by the larger coefficients on the graph.

[23] In **Appendix Figure A5**, I show that the results remain robust to an alternative definition of the move-out year.
[24] In **Appendix Figure A1** and **Table A1**, I repeat the analysis at the technology-class level, which confirms an increase in innovation activities in the EV domain following the ZEV mandate.

5.2. Firms in Adjacent Technological Domains (i.e., Affected Firms) Become Less Innovative after the ZEV Mandate Due to Loss of Inventors to EV Firms

Having documented the increase in EV innovation activities by EV firms, in this section I present the main results, which show that firms in adjacent technological domains became less innovative following the ZEV mandate because they lost inventors to EV firms.

Table 3 Column (1) suggests that, following the ZEV mandate, firms in adjacent technological domains, on average, produced 1.98 fewer patents, which amount to a 27% decline among the affected firms. Furthermore, **Table 3 Columns (2)–(5)** suggest that these firms became 29% less innovative in their core technological areas, 24% less innovative in their peripheral technological areas, 22% less likely to explore new technological areas, and 11% less original in future patents.

I examine the timing of this effect in **Figure 2** to confirm that the affected firms' decline in innovation occurred after the ZEV mandate. **Figure 2(a)** plots the yearly average number of patent counts—normalized to their pre-ZEV mandate levels, respectively—by affected and control firms.[25] The only transformation in **Figure 2(a)**, normalization of the dependent variable based on pre-event values, is made to account for the different absolute levels of patenting across firms. In **Figure 2(b)**, I plot the estimated difference in patent count between affected and control firms in each year, relative to the same difference in 1990. The graphs show that the difference in patent count between affected and control firms was small and stable before the ZEV mandate in 1990, but afterward the affected firms became less innovative than the control firms, as evidenced by the negative coefficients on the graph.

As shown in **Table 4**, the affected firms became less innovative because they experienced a greater loss of inventors to the EV firms after the ZEV mandate. Specifically, **Table 4 Column (1)** suggests that the affected firms lost on average 0.87 more inventors after the ZEV mandate—a level of loss more than 6.3 times greater—relative to the control firms. (The average number of net inventor loss per firm per year is 0.13, and

[25] In **Figure 2(a)**, the sharp increase after 1985 is because the sample is restricted to firms with at least three patents during 1986–1990. The decline immediately after 1990 is driven partly by some firms dropping out of the sample. As an additional check, I repeated the analysis, restricting the sample to firms with at least three patents during 1991–1995. **Figure A3** presents the results, showing that the sharp decline disappears and the results remain robust.

the average number of inventors per firm during the three years 1988–1990 was nine).[26] Furthermore, in **Column (2)** and **Column (3)**, I investigate the destination firms to which the affected firms lost inventors. I split the destination firms of the mobile inventors into EV and non-EV firms. **Column (2)** suggests that about 38% of the inventor loss was to the EV firms identified above in policy reports. In addition, **Column (3)** suggests that another 62% of the inventor loss was to EV firms that were not identified in the policy reports but that had at least one patent in the EV domain after the ZEV mandate (i.e., 1991–2000).

I examine the timing of this effect in **Figure 3**. In **Figure 3(a)** the raw data is used to plot the yearly average net inventor loss by affected and control firms. In **Figure 3(b)**, I plot the estimated difference between affected and control firms in the number of inventors lost each year, relative to the same difference in 1990. The difference between the affected and control firms was small and stable before the 1990 ZEV mandate, but afterward the affected firms experienced greater inventor loss than the control firms, as evidenced by the larger coefficients on the graph.

Taken together, **Tables 3 and 4** support the idea that increased demand for technologies in the EV domain negatively impacted the affected firms' rate and direction of innovation, because these firms lost more inventors to EV firms. Notably, both innovation in core technological areas and exploration of new technological areas declined among affected firms and their future innovations were less original. This indicates that inventors who left took with them not only their own skills but also other knowledge of value to the firms' innovation.

5.3. Heterogeneity by Affected Firms' Technological Domains, Size, and Age

After demonstrating that affected firms were less innovative after losing inventors to EV firms, I explore the heterogeneity of the main effects by the affected firms' respective technological domains, age, and size. Understanding these heterogeneous effects is important: they shed light on whether specific types of affected

[26] The effect sizes increase when I restrict the sample to the subset of affected firms that were more heavily impacted by the ZEV mandate (see **Table 7**).

firms were more adversely impacted and on potential implications for inequalities in innovation outcomes across firms and technological domains.

Heterogeneity by Technological Domains of Affected Firms. I examine which affected firms were more (or less) adversely impacted by the ZEV mandate: those in growing or declining technological domains. Following Tandon and Toh (2022), I identify each affected firm's respective technological domains as the set of CPC subclasses to which the firm's patents were assigned during the three years prior to the ZEV mandate (1988–1990). I then measure changes in technological opportunities within these domains by calculating the difference in the total number of patents filed by all institutions in the relevant CPC subclasses over the same period. Specifically, for each affected firm's respective CPC subclasses, I calculate this change as the total number of patents filed in 1990 minus the total filed in 1988. Finally, I categorize an affected firm as operating in a growing technological domain if the increase in patents within its domains from 1988 to 1990 exceeds the median increase observed across the domains of all affected firms.[27]

Next, I examine whether affected firms in other emerging domains, such as renewable energy, were more (or less) adversely impacted. I consider affected firms that had at least three patents in CPC subclass Y02E10 (Energy Generation through Renewable Energy Sources) prior to the ZEV mandate to be more actively engaged in renewable energy domains.[28] This subclass includes patents on clean technologies such as photovoltaic energy, hydro energy, and wind energy.

Table 5 Columns (1) and (2) present the results. **Column (1)** suggests that affected firms in growing technological domains were more likely to lose inventors to EV firms, relative to other affected firms. In particular, **Column (2)** suggests that affected firms in emerging renewable energy domains—such as photovoltaic energy, hydro energy, and wind energy—were even more likely to lose inventors. In Appendix **Tables A5 and A6**, I show that this is likely because the EV domain was an emerging and growing technological domain. Consequently, affected firms in other emerging and growing domains, such as renewable energy, were

[27] The results are robust to other cutoffs, such as top quartile or when using a continuous measure.
[28] The results are robust to other cutoffs.

more likely to have originally hired inventors with expertise closely related to EV technologies, making these firms more susceptible to losing inventors.

Heterogeneity by Size and Age of Affected Firms. I also examine whether smaller (or larger) and younger (or older) firms were more adversely impacted by the ZEV mandate; I measure a firm's size by its number of inventors during 1986–1990, and its age by the number of years from its first patent until 1990. **Table 5 Columns (3) and (4)** present the results. In these regressions, I replace the dependent variable with the share of inventor outflow to better capture the impact on firms of different sizes and ages.[29] This adjustment accounts for the fact the baseline number of inventors who can be lost is greater for older and larger firms. **Column (3)** suggests that smaller firms were relatively more likely to lose inventors than larger firms. Meanwhile, **Column (4)** suggests that younger firms may have been more likely to lose inventors than older firms, though this result is not statistically significant. In **Appendix Table A2**, I conduct a split-sample analysis by firm size and age, and the results are consistent with the interaction results. Overall, the findings suggest that smaller and younger firms were at least equally, if not more, affected by the ZEV mandate.

In summary, these results suggest that firms in growing technological domains—especially renewable energy domains—and smaller, younger firms were more adversely (or at least equally) affected by the increase in demand for EV technologies. These findings are potentially concerning, as they indicate that the growth of EV domains may have come, at least in part, at the expense of other emerging domains and that of smaller, younger startups, whose innovations could have significant implications for societal benefits.

6. Mechanism

6.1. Affected Firms Become Less Innovative *Because* They Lose Inventors to EV Firms

So far, the main results suggest that, after the ZEV mandate, firms in adjacent technological domains lost more inventors to EV firms and became less innovative. However, we still lack direct evidence that these affected

[29] Specifically, I divide the net inventor outflow in each year by the firm's number of inventors during 1986–1990. Using the number of inventors before the shock as the denominator ensures that this measure remains unaffected by changes following the ZEV mandate and provides a consistent baseline for comparison.

firms became less innovative precisely because they lost inventors. This section provides direct evidence and triangulates it using two approaches.

First, I repeat the main analysis with a subgroup of affected firms that lost at least one inventor after the ZEV mandate (1991–2000), and another subgroup of firms that did not lose inventors. **Table 6** presents the results, which show that the main results (i.e., a decline in innovation) were driven by affected firms that lost at least one inventor during 1991–2000 (**Column [1]**), rather than by firms that did not lose inventors (**Column [2]**). However, the results in **Table 6** should be interpreted as suggestive correlations, as the grouping of affected firms is based on their inventor loss following the ZEV mandate, and unobservable factors may have simultaneously driven both inventor loss and the decline in innovation.

As a second approach, I repeat the main analysis with a subgroup of affected firms that had hired inventors with expertise relevant for the EV domain; I expect the main effects to be stronger among these firms.[30] The main rationale is that inventors with expertise closer to the EV domain were likely to have been in higher demand by EV firms than inventors lacking relevant EV expertise).[31] As a result, I expect affected firms that originally hired these inventors to have been more negatively affected by the increase in EV innovation activities.

To test this, I identify inventors who patented in the adjacent technological domains during 1986–1990 (the five-year period before the ZEV mandate), restricting inventors to those with at least one patent after the ZEV mandate.[32] This process results in 43,673 "at-risk" inventors for whom I construct a measure of their technological proximity to the EV domain. Specifically, I collect each inventor's patents filed during 1986–1990 and aggregate the patents to the four-digit CPC subclass level. This subclass distribution of patents thus characterizes the inventor's domain of knowledge during 1986–1990. I then calculate each inventor's technological proximity to the EV domain as the cosine similarity between the CPC subclass distribution of

[30] The identification assumption here is that the distribution of these inventors during 1986–1990 is uncorrelated with the adoption of the ZEV mandate in 1990.
[31] I provide evidence for this in **Section 6.2**.
[32] I do this to ensure that the results are not driven by inventors who stopped patenting following the mandate.

their patents and the CPC subclass distribution of the EV patents.[33] Therefore, if an inventor has a higher cosine similarity measure, that inventor's domain of knowledge is considered relatively closer to the EV domain than that of another inventor with a lower cosine similarity measure. After constructing this measure, I further group the at-risk inventors into four quartiles based on their technological proximity to EV.[34]

To provide direct evidence that the affected firms' decline in innovation was driven by their loss of inventors to EV firms, I group the affected firms into those that hired inventors with expertise close to the EV domain before the ZEV mandate versus other affected firms that did not hire these inventors. **Table 7** presents the results. Specifically, in **Columns (1)** and **(2)**, I repeat Equation (2) but restrict affected firms to those hiring at least one inventor whose technological proximity to EV was in the top quartile (i.e., top quartile inventors), whereas in **Columns (3)** and **(4)**, I restrict affected firms to those ones hiring at least one inventor whose technological proximity to EV was in the top 50th percentile.[35] The results suggest that affected firms that had originally employed inventors with expertise closer to EV were indeed more negatively affected by the increase in demand for EV (**Columns [1]-[4]**), and the effects were especially stronger for firms that had hired inventors with expertise very close to EV (**Columns [1]** and **[2]**).

Columns (5) and **(6)** further restrict the affected firms to those whose inventors were all far from the EV domain during 1986–1990; specifically, these firms did not employ any inventors with proximity to EV above the bottom quartile (25th percentile). Presumably, these firms should have been the least affected by the increase in demand for EV technologies, simply because their inventors were less sought after by EV firms. Indeed, the results become insignificant, thereby providing additional support for my main findings.

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[33] Specifically, I collected each inventor's patents during 1986–1990 and their corresponding four-digit CPC subclasses. I then calculated the distribution vector of each inventor's patents across these subclasses. Similarly, I collected all EV patents during 1986–1990 and their corresponding four-digit CPC subclasses and calculated their distribution vector. Next, I calculated the cosine similarity between the two vectors (Benner and Waldfogel, 2008). Formally, I calculate: $\frac{\Sigma_k p_{ik} pEV_k}{\sqrt{\Sigma_k p_{ik}^2 \Sigma_k pEV_k^2}}$, where i is an at-risk inventor, and p_{ik} is the vector representing the percentage of the inventor's patents in subclass k, and pEV_k is the vector representing the percentage of EV patents in subclass in subclass k.

[34] In **Section 6.2**, I show that at-risk inventors whose EV adjacency were in the top quartile were about 17.3% more likely to leave an affected firm and join an EV firm after the ZEV mandate, relative to inventors in the bottom quartile.

[35] Results remain robust to other cutoff number of inventors, such as two, three, five or ten inventors in the top quartile or top 50th percentile.

Figure A2 illustrates the timing of the effects by repeating **Figures 2** and **3** using each of the firm subsamples. Specifically, in **Figure A2.1**, where affected firms are restricted to those ones hiring at least one inventor with expertise very close to the EV domain, the trends replicate the main results in **Figures 2** and **3** with stronger effects. In comparison, in **Figure A2.3**, where affected firms are restricted to those whose inventors during 1986-1990 were all far from the EV domain, the effects disappear; these firms were not more likely to lose inventors or to become less innovative after the ZEV mandate, relative to the control firms.

In summary, the results in this section support the main results and offer direct evidence that after the ZEV mandate, which led to increased innovation activities in the EV domain, firms in adjacent technological domains became less innovative *because* these firms were more likely to have lost inventors to EV firms. In particular, affected firms were negatively impacted because they originally employed inventors whose knowledge and expertise were relevant for developing EV innovation; these inventors were thus in greater demand and were more susceptible to recruitment by EV firms following the ZEV mandate.

6.2. Individual-Level Evidence of Increased Inventor Loss Among Affected Firms

To further confirm the increased inventor loss among affected firms, this section provides additional evidence at the individual inventor level. Using the sample of 43,673 "at-risk" inventors who patented in the adjacent technological domains during 1986–1990, I explicitly examine whether those from firms in adjacent technological domains were more likely to leave their employers and join EV firms following the ZEV mandate. I estimate a difference-in-differences logit model with panel data at the inventor-year level for the years 1981–2000.

$$Move_{it} = \beta(EVAdjacency_i \times AfterZEV_t) + \gamma_i + \delta_t + \varphi PriorMove_{it} + \varepsilon_{it} \quad (3)$$

where i is the individual inventor, and the dependent variable $Move_{it}$ is an indicator variable equal to 1 if inventor i applied for a patent in year t and the patent has an assignee different from the inventor's previous patents, and 0 otherwise. $AfterZEV_t$ is an indicator variable equal to 1 for the years 1991–2000, namely after

the ZEV mandate, and 0 otherwise. $EVAdjacency_i$ is a *continuous treatment* measure equal to inventor i's technological proximity to the EV domain as calculated in Section 6.1. A higher measure indicates that inventor i's domain of knowledge was closer to the EV domain, relative to that of an inventor with a lower measure. The terms γ_i and δ_t capture inventor fixed effects and year fixed effects. $PriorMove_{it}$ captures whether the inventor had moved previously (Marx, Strumsky and Fleming, 2009).

Table 8 presents the results. **Column (1)** suggests that inventors from firms in adjacent domains with expertise closer to the EV domain were more likely to change employers after the ZEV mandate than were inventors farther from the EV domain. To quantify the magnitude, I repeat the regression using a dummy treatment variable, assigning an at-risk inventor to the treatment group if their technological proximity to the EV domain is in the top quartile, and to the control group if their technological proximity is in the bottom quartile. The result suggests that inventors in the top quartile of closeness to the EV domain were 17.3% more likely to have changed employers after the mandate, relative to control inventors in the bottom quartile. **Figure 4** plots the year-specific differences using this dummy treatment variable and provides support for the parallel trend assumption.

In **Columns (2)** and **(3)**, I repeat the regressions with the dependent variable being the propensity to move from a non-EV employer to an EV employer in a year (**Column [2]**) and the propensity to move from EV employer to non-EV employer (**Column [3]**). The results confirm that the main results of greater inventor loss are indeed driven by inventors moving from firms in adjacent technological domains to EV firms. Lastly, I find that these inventors were more likely to engage in EV innovations after the ZEV mandate (**Column [4]**). In **Appendix Table A7**, I provide additional evidence through a split-sample analysis and show that the increased inventor mobility was driven by inventors who moved to EV firms after 1990 (**Table A7 Column [2]**), and not by inventors already in the EV domain. In fact, if an inventor was already working on EV innovations for an EV employer before 1990, that inventor was less likely to change employers after the ZEV mandate (**Table A7 Column [5]**).

In summary, **Table 8** offers additional evidence at the individual inventor level and confirms that after the increase in demand for EV technologies, firms in adjacent technological domains became less innovative *because* they lost more inventors to EV firms.

7. Robustness Checks and Additional Analysis

In the main results, I find that, after the ZEV mandate, firms in adjacent technological domains were 27% less innovative, particularly in their core technological areas; they also were 22% less likely to explore new technological areas. This decline in innovation occurred because these affected firms lost more inventors to EV firms following the increased demand for EV technologies.

In this section, I report additional robustness checks to confirm that the main results remain robust to alternative explanations and empirical specifications (See Appendix A for a more detailed interpretation of the results). First, in **Appendix Figure A3** and **Table A3**, I show that the results are robust and stronger when the sample is restricted to firms with at least three patents during 1991–1995. Next, I show that the main results are robust to alternative cutoff definitions of adjacent firms (**Figure A4**), to alternative definitions of move-out years (**Figure A5**), and to alternative model specification (Poisson model; **Figure A6**); the results are not fully explained by movement to subsidiary firms (**Table A4 Column (2)**), mergers and acquisitions (M&A; **Figure A7**), or public funding (**Figure A8**).

8. Conclusion

8.1. Discussion and Contribution

Innovation is critical to a firm's competitive advantage and, more broadly, to economic growth. Knowledge workers are the engines that power a firm's ability to innovate. This study examines how changes in downstream market demand within a technological domain may adversely affect the rate and direction of innovation by firms in adjacent domains by reshaping the competitive landscape for knowledge workers.

Empirically, I exploit the unanticipated ZEV mandate, which led to an exogenous increase in demand for EV technologies. Following the ZEV mandate, EV firms increased EV innovation activities. However, this

increase negatively affected the rate and direction of innovation among adjacent firms. Specifically, firms in adjacent domains became 26% less innovative, particularly in their core technological areas, and they were 22% less likely to explore new technological areas after the ZEV mandate, relative to firms not in adjacent domains. This occurred because they were 670% more likely to lose inventors to EV firms. Additional analyses reveal that adverse effects were greater for firms more active in growing technological domains—especially renewable energy domains—and for smaller, younger firms.

This study makes several contributions. First, it extends the literature on the determinants of innovation. A central discussion in the innovation literature has been on the origins of innovation. In particular, the demand-pull literature has highlighted the crucial role of downstream market demand in driving innovation within a technological domain and has uncovered various mechanisms through which demand spurs innovation activities (Mowery and Rosenberg, 1979; Adner and Levinthal, 2001; Fabrizio and Thomas, 2012; Byrski, Gaessler, and Higgins, 2021; Galasso and Luo, 2021). This study expands this line of work by drawing attention to an important yet understudied constraint on innovation: The immediate supply of new knowledge workers may not be sufficient to meet the increase in innovation activities driven by the demand. By accounting for this inelastic supply of knowledge workers, this study finds that while an increase in downstream market demand can directly drive *positive* innovation progress in a demand-relevant domain, it may also create indirect *negative* spillover effects on the innovation progress of firms in *adjacent technological domains* through intensifying the competition for knowledge workers. Therefore, this study extends the focus of existing research on the direct positive effect of market demand on innovation. It allows a more comprehensive understanding of the direct and indirect impacts of market demand on innovation in different domains, offering a more holistic view of how changes in market demand shape the evolution of the broader technological landscape.

Second, this study connects demand-pull literature with the worker-mobility literature. Prior research in the worker-mobility literature has addressed the consequences of worker loss (Campbell et al., 2012). However, this study extends the focus on worker loss by integrating insights from the demand-pull literature. In particular, these findings reveal how market and technological changes in seemingly unrelated industries and technological domains can unexpectedly cause a firm to lose inventors, which can ultimately undermine the

firm's technological capabilities. Understanding this is particularly timely and important given the rapid emergence of fast-growing, R&D-intensive industries such as artificial intelligence, quantum computing, and electric and autonomous vehicles, which have accelerated market and technological changes, intensifying competition for knowledge workers (*Wall Street Journal*, 2015a; *Wall Street Journal*, 2015b; *New York Times*, 2023). Therefore, this study provides novel insights into how shifts in other industries and domains may impact a focal firm through the loss of workers or resources

Relatedly, recent studies in the innovation literature highlight the important role of high-skilled knowledge for firms' innovation progress (Roach and Skrentny, 2019; Ganco, Miller, and Toh, 2020; Miric and Ozalp, 2020; Dimmock, Huang, and Weisbenner, 2022; Roach and Sauermann, 2023). Other studies have focused on how firms can maximize their learning from these hired workers through mechanisms such as effective team and organizational design (e.g., Choudhury and Haas, 2018; Chang, 2023). However, most studies in this literature have focused on how firms can benefit from hiring skilled knowledge workers to enhance their innovation progress with less attention paid to firms that lose these workers and the associated innovation consequences. In R&D-intensive industries where the supply of high-skilled knowledge workers is often inelastic, one firm's gain of knowledge workers is often another's loss. Understanding which firms (in which technological domains) lose workers has important literature and practical implications. This study contributes by shedding light on how growth in one technological domain may shape the competitive landscape for high-skilled knowledge workers and by uncovering the innovation consequences for firms losing workers. In particular, finding that firms in growing technological domains were more adversely affected has important implications for the broader impacts of worker mobility on innovation.

Furthermore, this study relates to research that investigates the allocation of innovation resources and the associated implications for societal benefits (Bryan and Lemus, 2017; Bryan and Williams, 2021; Hopenhayn and Squintani, 2021; Acemoglu, 2023; Goldfarb, Lu, and Teodoridis, 2025). Studies in this literature suggest that firms often allocate excessive innovation resources toward technologies that are immediately profitable and underinvest in emerging technologies that are socially valuable but not immediately profitable, a pattern that is not optimal for long-term societal benefits. Because of this, policy interventions by the public sector,

including various demand-side policies, tax subsidies, and procurement, have often been viewed as solutions to drive technological progress in emerging technologies. However, the findings in this study suggest that policymakers' explicit decisions to support a particular emerging technology may adversely affect other growing and emerging technologies, especially when the innovation resources (e.g., the knowledge and expertise of skilled workers) are transferable across domains. This study does not conclude that policymakers should refrain from adopting such innovation policies; instead, these findings should encourage policymakers to think more broadly about the potential indirect spillover effects when designing innovation policies.

These findings also have important managerial implications. Skilled knowledge workers are the engines that power firms' ability to achieve technological advancements and build competitive advantages. The findings in this study highlight the fact that market and technological changes in seemingly unrelated areas can create competition for knowledge workers that indirectly erodes a firm's technological capabilities. It is crucial that managers understand these dynamics to anticipate when worker loss may occur and, more broadly, to appreciate how market and technological changes in other industries and domains can affect their firms through loss of workers or resources. With the rapid emergence of R&D-intensive industries—and the accelerated pace of technological change in recent years—this study offers timely and critical insights for managers.

8.2. Limitation and Future Research

The empirical results in this study are not without limitations and therefore require careful interpretation. First, prior studies have suggested potential limitations to inferring inventor mobility when using changes in assignee information between consecutive patent applications. For example, this method may fail to capture inventors who moved but did not patent afterward (i.e., false negatives). To address these concerns, I conducted extensive mechanism analyses and robustness checks to ensure that my main results are not fully explained by such alternative explanations. Moreover, I argue that this concern is more likely to lead to an underestimation of the true effects rather than to an overestimation; if some inventors moved to EV firms but did not patent afterward, the true effect of increased demand for EV technologies on inventor loss among affected firms would be greater than the current estimate, not smaller.

Second, it is possible that the findings of this study are subject to some idiosyncratic aspects of this setting. For example, one advantage of using the ZEV mandate as an empirical setting is that it imposed a sales requirement for electric vehicles. At the same time, the EV industry was still emerging in the 1990s, when there may have been a talent gap. This context allows the study to isolate the negative spillover effects of market demand on innovation by highlighting competition for innovation resources—especially for knowledge workers—an area that has been less studied in the literature. However, it is possible that in other contexts—such as when increased innovation activities are more driven by technology-push (rather than demand-pull) factors, or when labor supply is more abundant—the negative spillover effects may be tempered by other forces, such as knowledge spillovers, and therefore may be harder to isolate. Thus, this research represents a first step in this line of inquiry, and future research can further explore these dynamics and extend the findings to other settings.

Third, in this study, I identified the EV firms based on CARB's policy reports and studies of the ZEV mandate, which are authoritative documents evaluating progress in EV technologies during the 1990s. Consequently, the EV firms were identified ex post, meaning they were recognized based on their mention in these reports that document key players in EV technologies after the mandate. Some EV firms, such as EV component suppliers, may have benefited from the EV demand opportunities and successfully diversified into the EV domain after the ZEV mandate. I adopted this approach to identify EV firms because firms' diversification decisions are often shaped by a range of nuanced and interdependent factors (such as the possession of complementary assets) (e.g., Wu, 2013; Wu, Wan, and Levinthal, 2014; Chang, Eggers, and Keum, 2022), rather than to explicitly examine ex ante which firms diversified into the EV domain, a question beyond the scope of this paper. Moreover, the intended contribution of this study is not to examine the determinants of firms' diversification decisions, but rather to highlight that, while increased market demand could drive innovation in the EV domain, it could also have adversely affected innovation of some firms in adjacent domains by intensifying competition for inventors. By presenting the main results along with careful robustness checks and mechanism analyses, this study draws attention to the understudied negative spillover effects of market demand on innovation driven by competition for innovation resources.

More broadly, by drawing attention to the negative spillover effects of market demand on innovation progress in adjacent technological domains, this study opens avenues for future research. For instance, does this negative spillover affect all firms equally? What are the short-term versus long-term effects? How can firms mitigate the risk of losing resources and knowledge workers? How might policymakers mitigate these negative spillovers? Exploring these questions is important for both advancing theoretical understanding and for informing practical implications for firms and policymakers. To this end, I hope this study encourages future research to build on and extend its findings.

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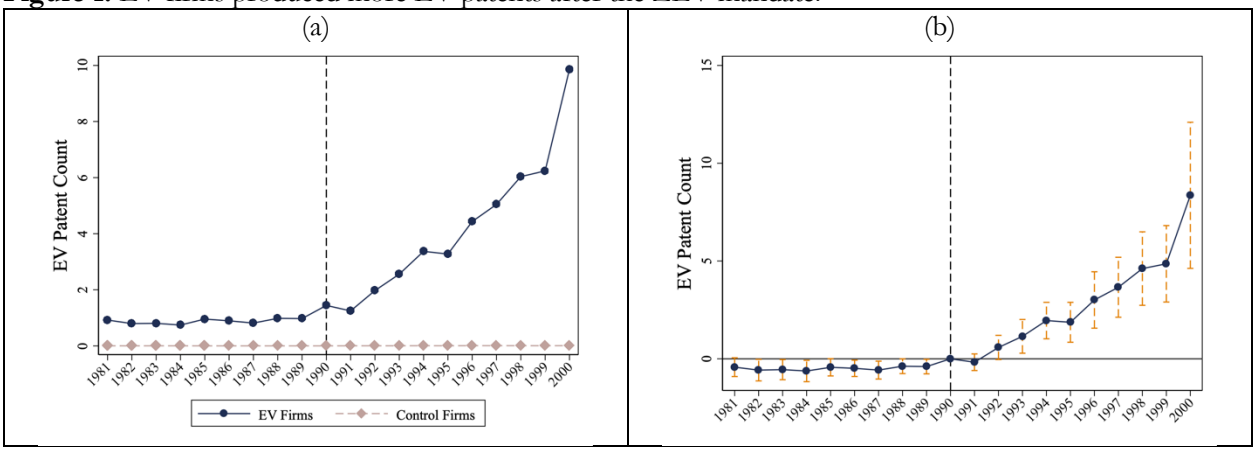
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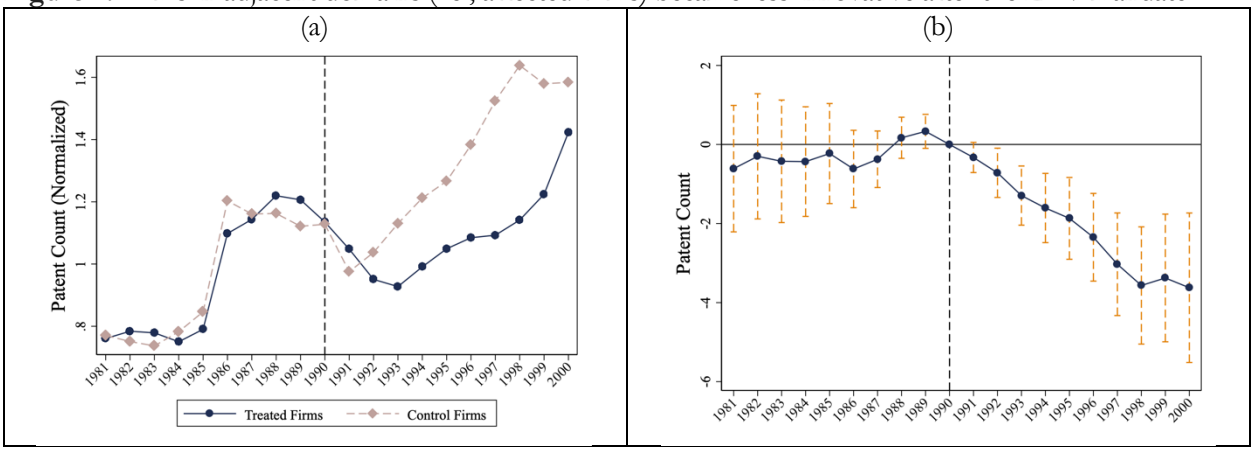
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Figure 1. EV firms produced more EV patents after the ZEV mandate.



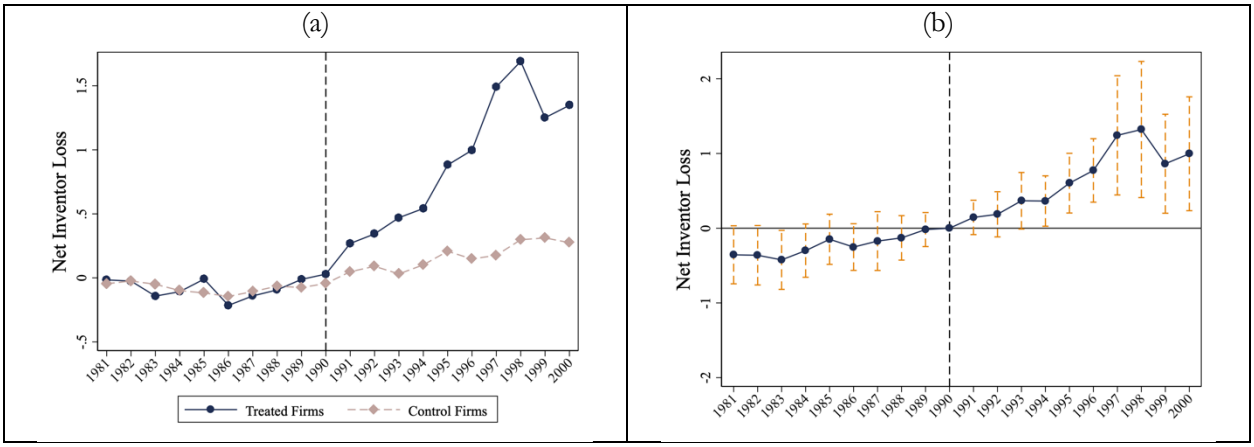
Note. **Figure (a)** plots the raw data. The solid line plots the yearly average number of EV patents by EV firms, whereas the dotted line plots the yearly average number of EV patents by control firms. The dotted line remains close to zero because the control firms had few EV patents. In **Figure A9**, I present a version of this graph with EV patent counts normalized to their pre-ZEV mandate levels. **Figure (b)** plots the difference-in-differences coefficient value. Each point on the graph represents the coefficient value on the covariate *EV Firm*×*Year* and thus describes the relative difference between EV firms and control firms in the number of EV patents in that year. The bars surrounding each point represent the 95% confidence interval. All values are relative to the base year, 1990. EV firms are identified using CARB's policy reports and studies on the ZEV mandate, which are authoritative documents evaluating progress in EV technologies during the 1990s. I use the same control firms used for the main analysis: Specifically, these are firms that had not patented in adjacent subclasses before the ZEV mandate, but had overlapped with the affected firms in other three-digit patent subclasses before the ZEV mandate (1986–1990).

Figure 2. Firms in adjacent domains (i.e., affected firms) became less innovative after the ZEV mandate.



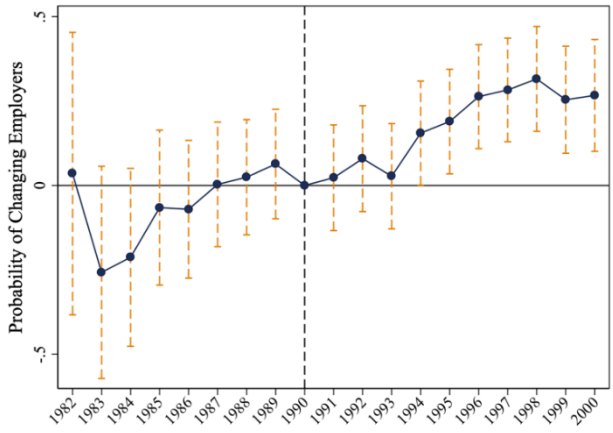
Notes. **Figure (a)** plots the raw patent count, normalized to their pre-ZEV mandate levels. The solid line plots the yearly average normalized number of patents by affected firms, whereas the dotted line plots the yearly average normalized number of patents by control firms. There is a sharp increase after 1985 because I restricted the sample to firms with at least three patents during 1986–1990 (this restriction allows me to characterize the technological domains of each firm more accurately). The decline immediately after 1990 is driven partly by some firms dropping out of sample after 1990. As an additional check, I repeat the analysis in **Figure A3**, restricting firms to those with at least three patents during 1991–1995. The results remain robust. **Figure (b)** plots the difference-in-differences coefficient value. Each point on the graph represents the coefficient value on the covariate *Affected Firm*×*Year* and thus describes the relative difference between affected and control firms in the number of patents in that year. The bars surrounding each point represent the 95% confidence interval. All values are relative to the base year of 1990. Affected firms are defined as firms with at least 10% of their patents in subclasses adjacent to the EV subclasses within the five years before the ZEV mandate (1986–1990). Control firms are firms that did not patent in adjacent subclasses before the ZEV mandate but overlapped with the affected firms in other three-digit patent subclasses before the ZEV mandate (1986–1990). Thus, the control firms are technologically close to the affected firms but are relatively farther from the EV technologies.

Figure 3. Affected firms (became less innovative because they) experienced a greater loss of inventors after the ZEV mandate.



Notes. **Figure (a)** plots the raw data. The solid line plots the yearly average net inventor loss by affected firms, whereas the dotted line plots corresponding yearly average net inventor loss by control firms. **Figure (b)** plots the difference-in-differences coefficient value. Each point on the graph represents the coefficient value on the covariate *Affected Firm*×*Year* and thus describes the relative net difference between affected and control firms in the numbers of inventors lost in that year. The bars surrounding each point represent the 95% confidence interval. All values are relative to the base year of 1990. Affected firms are defined as firms with at least 10% of patents in patent subclasses adjacent to EV subclasses within five years before the ZEV mandate (1986–1990). Control firms are firms that did not patent in the adjacent subclasses before the ZEV mandate but overlapped with affected firms in other three-digit patent subclasses before the ZEV mandate (1986–1990). Thus, the control firms are technologically close to the affected firms but are relatively farther from the EV technologies.

Figure 4. Inventors with expertise closer to EV were 17.3% more likely to change employers (and join EV firms) after the ZEV mandate.



Notes. This figure plots the difference-in-differences coefficient estimates. Each point on the graph represents the coefficient value on the covariate *EV adjacency*×*Year* and thus describes the relative difference between the treatment and control groups in the likelihood of changing employers in that year. The treatment group is those inventors with cosine similarity to EV subclasses in the top quartile, and the control group is those inventors with cosine similarity in the bottom quartile. The bars surrounding each point represent the 95% confidence interval. All values are relative to the base year of 1990.

Table 1. Descriptive statistics

Variable	Mean	Std. dev	Minimum	Maximum	Obs
Firm-year panel (for baseline analysis to confirm increased EV innovation activities by EV firms)					
EV patent count	0.07	1.27	0.00	130.00	85,840
Age	10.43	8.28	-18.00	50.00	85,840
After ZEV mandate	0.50	0.50	0.00	1.00	85,840
EV firm	0.08	0.48	0.00	3.00	85,840
Firm-year panel (for main analysis using affected firms)					
Net inventor outflow	0.14	3.84	-276.00	364.00	91,867
Patent count	3.75	19.19	0.00	1586.00	91,867
Patent count in core technological areas	2.52	13.43	0.00	1003.00	91,867
Patent count in peripheral technological areas	1.23	7.18	0.00	583.00	91,867
Count of new technological areas	1.10	2.50	0.00	59.00	84,128
Average originality of patent	0.25	0.31	0.00	0.95	91,867
Firms in growing technological domains	0.51	0.50	0.00	1.00	91,867
Firms in renewable energy domains	0.01	0.12	0.00	1.00	91,867
Small firms (i.e., firm inventor count below median (1986–1990))	0.48	0.50	0.00	1.00	91,867
Small firms (i.e., firm age in 1990 less than 8 years)	0.36	0.48	0.00	1.00	91,867
Age	12.20	7.06	0.00	50.00	91,867
After ZEV mandate	0.56	0.50	0.00	1.00	91,867
Affected firm	0.19	0.39	0.00	1.00	91,867
Inventor-year panel (for mechanism analyses)					
Move	0.08	0.28	0.00	1.00	678,766
EV patent count	0.02	0.22	0.00	31.00	678,766
Prior move	0.36	0.48	0.00	1.00	678,766
After ZEV mandate	0.60	0.49	0.00	1.00	678,766
Affected inventors	0.50	0.29	0.00	1.00	678,766

Table 2. EV firms produced more EV patents after the ZEV mandate.

DV: EV Patent Count	(1)
EV firm × After ZEV mandate	**3.433*** (0.633)**
R^2	0.080
Observations	85,840
Age Control	Yes
Firm FE	Yes
Year FE	Yes

Notes. The data are a panel at the firm-year level based on patent data for 1981–2000. EV firms are identified using CARB's policy reports and studies on the ZEV mandate, which are authoritative documents evaluating progress in EV technologies during the 1990s. I use the same control firms used for the main analysis. Specifically, control firms did not patent in adjacent subclasses before the ZEV mandate but overlapped with affected firms in other three-digit patent subclasses before the ZEV mandate (1986–1990). OLS with robust standard errors are clustered at the firm level. Estimations presented as coefficient (SE).
*p < 0.10; **p < 0.05; ***p < 0.01.

Table 3. Firms in adjacent domains (i.e., affected firms) became less innovative after the ZEV mandate.

	(1) DV: Patent count	(2) DV: Patent count in core technological areas	(3) DV: Patent count in peripheral technological areas	(4) DV: Count of new technological areas	(5) DV: Average patent originality
Affected firm × After ZEV mandate	**-1.980*** (0.553)**	**-1.303*** (0.350)**	**-0.678*** (0.240)**	**-0.623*** (0.092)**	**-0.046*** (0.008)**
R^2	0.003	0.002	0.003	0.014	0.035
Observations	91,867	91,867	91,867	84,128	91,867
Age control	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes

Notes. The data are a panel at the firm-year level based on patent data for 1981–2000. Different columns correspond to different definitions of dependent variables. Affected firms are firms with more than 10% of patents in patent subclasses adjacent to EV subclasses within five years before the ZEV mandate (1986–1990). Control firms are defined as firms that did not patent in adjacent subclasses before the ZEV mandate but overlapped with the affected firms in other three-digit patent subclasses before the ZEV mandate (1986–1990). Thus, the control firms are technologically close to the affected firms but are relatively farther from the EV technologies. All models are OLS with robust standard errors clustered at the firm level. Estimations presented as coefficient (SE).
*p < 0.10; **p < 0.05; ***p < 0.01.

Table 4. Affected firms (became less innovative because they) experienced a greater loss of inventors after the ZEV mandate.

	(1) DV: Net inventor loss	(2) DV: Net inventor loss to EV firms (identified in policy documents)	(3) DV: Net inventor loss to other firms that produced EV innovations after ZEV mandate	(5) DV: Net inventor loss to non-EV firms
Affected firm × After ZEV mandate	**0.872*** (0.204)**	**0.341*** (0.125)**	**0.553*** (0.131)**	**-0.103 (0.092)**
R^2	0.008	0.003	0.003	0.002
Observations	91,867	91,867	91,867	91,867
Age control	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Notes. The data are a panel at the firm-year level based on patent data for 1981–2000. Different columns correspond to different definitions of dependent variables. Affected firms are defined as firms that had at least 10% of patents in patent subclasses adjacent to the EV subclasses within five years before the ZEV mandate (1986–1990). Control firms are defined as firms that did not patent in adjacent subclasses before the ZEV mandate but overlapped with the affected firms in other three-digit patent subclasses before the ZEV mandate (1986–1990). Thus, the control firms are technologically close to the affected firms but are relatively farther from the EV technologies. All models are OLS with robust standard errors clustered at the firm level. Estimations presented as coefficient (SE).
*p < 0.10; **p < 0.05; ***p < 0.01.

Table 5. Heterogeneity of main effects by technological domains, firm size, and firm age.

	DV: Net Inventor Outflow		DV: Share of Inventor Outflow	
Affected firm × After ZEV mandate × Firm in growing technological domains	**1.242*** (0.358)**			
Affected firm × After ZEV mandate × Firm in renewable energy domains		**7.211** (3.677)**		
Affected firm × After ZEV mandate × Firm inventor count below median (1986–1990)			**0.020** (0.009)**	
Affected firm × After ZEV mandate × Firm age in 1990 less than 8 years				**0.006 (0.008)**
R^2	0.010	0.015	0.002	0.004
Observations	91,867	91,867	91,867	91,867
Age control	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Notes. The data are a panel at the firm-year level based on patent data for 1981–2000. Different columns correspond to different definitions of dependent variables. Affected firms are defined as firms with at least 10% of patents in patent subclasses adjacent to EV subclasses within five years before the ZEV mandate (1986–1990). Control firms are defined as firms that did not patent in adjacent subclasses before the ZEV mandate but overlapped with affected firms in other three-digit patent subclasses before the ZEV mandate (1986–1990). Thus, the control firms are technologically close to the affected firms but are relatively farther from the EV technologies. All models are OLS with robust standard errors clustered at the firm level. Estimations presented as coefficient (SE).
*p < 0.10; **p < 0.05; ***p < 0.01.

Table 6. Affected firms' decline in innovation is driven by inventor loss.

DV: Patent count	(1) Subsample: Firms whose count of net inventor loss during 1991–2000 is greater than zero	(2) Subsample: Firms whose count of net inventor loss during 1991–2000 is equal to 0
Affected firm × After ZEV mandate	**-2.001*** **	**0.012**
	(0.623)	**(0.134)**
R^2	0.017	0.022
Observations	55,832	15,699
Firm FE	Yes	Yes
Year FE	Yes	Yes

Notes. The data are a panel at the firm-year level based on patent data for 1981–2000. Different columns correspond to different subsamples. All models are OLS with robust standard errors clustered at the firm level. Estimations presented as coefficient (SE).
*p < 0.10; **p < 0.05; ***p < 0.01.

Table 7. Main results of inventor loss and decline in innovation are driven by affected firms that hired inventors with expertise close to EV technologies.

	Affected firms restricted to those hiring at least one inventor with expertise very close to EV tech (i.e., proximity in the top quartile) during 1986–1990		Affected firms restricted to those hiring at least one inventor with expertise relevant to EV tech (i.e., proximity above the top 50th percentile) during 1986–1990		Affected firms restricted to those whose inventors during 1986-1990 had no expertise close to EV tech	
	(1) DV: Net inventor loss	(2) DV: Patent count	(3) DV: Net inventor loss	(4) DV: Patent count	(5) DV: Net inventor loss	(6) DV: Patent count
Affected firm × After ZEV mandate	**2.244*** (0.558)**	**-3.937*** (1.276)**	**1.356*** (0.303)**	**-2.654*** (0.745)**	**-0.104 (0.102)**	**-0.232 (0.680)**
R^2	0.011	0.003	0.009	0.003	0.004	0.003
Observations	80,531	80,531	85,929	85,929	77,058	77,058
Age control	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes. The data are a panel at the firm-year level based on patent data for 1981–2000. Different columns correspond to different definitions of dependent variables and subsamples. All models are OLS with robust standard errors clustered at the firm level. Estimations presented as coefficient (SE).
*p < 0.10; **p < 0.05; ***p < 0.01.

Table 8. Inventors (from affected firms) who had expertise closer to the EV domain were more likely to change employers after the ZEV mandate.

	(1) DV=1 if changed employer in a year	(2) DV = 1 if moved from non-EV employer to EV employer	(3) DV = 1 if moved from EV employer to non-EV employer	(4) DV: Number of EV patents
EV adjacency × After ZEV mandate	**0.255*** (0.048)**	**0.194** (0.083)**	**-0.029 (0.096)**	**0.016*** (0.002)**
LL/R^2	-80,861.498	-24,568.629	-18,810.026	0.003
Observations	420,765	138,350	114,042	639,840
Controls	Yes	Yes	Yes	Yes
Inventor FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Notes. The data are a panel at the **inventor-year level** based on patent data for 1981–2000. *EV adjacency* is a continuous treatment variable that captures an inventor's technological proximity to the EV domain. It is calculated as the cosine similarity measure between the CPC patent class distribution of an inventor's patents and the CPC patent class distribution of the EV patents. I calculate this measure using patents from 1986–1990. Columns (1)–(3) report results from a logit model and Column (4) reports results from an OLS model, with robust standard errors clustered at the inventor level. Estimations presented as coefficient (SE).
*p < 0.10; **p < 0.05; ***p < 0.01.

Appendix A. Robustness Checks and Additional Analyses

Note for Table A1 and Figure A1. I perform an analysis at the technology class level to confirm that the ZEV mandate led to an increase in innovation activities in the EV domain. I conduct a difference-in-differences analysis at the CPC patent subclass level. I define the treatment group as the nineteen patent subclasses directly related to EV technologies, and the control group as other non-EV subclasses under Y02T. Formally, I estimate a difference-in-differences OLS model with panel data at the patent subclass-year level for the years 1981–2000.

$$EVPatentCount_{jt} = \beta\left(EV\ subclass_j \times AfterZEV_t\right) + \gamma_j + \delta_t + \varepsilon_{jt}$$

where $EV\ subclass_j$ is a dummy variable equal to 1 if patent subclass j is an EV patent subclass, and 0 otherwise. $AfterZEV_t$ is an indicator variable equal to 1 for years after the ZEV mandate, and 0 otherwise. γ_j captures subclass fixed effects, and γ_t captures year fixed effects. The dependent variable $EVPatentCount_{jt}$ captures the number of EV patents (dated by application year) in patent subclass j in year t.

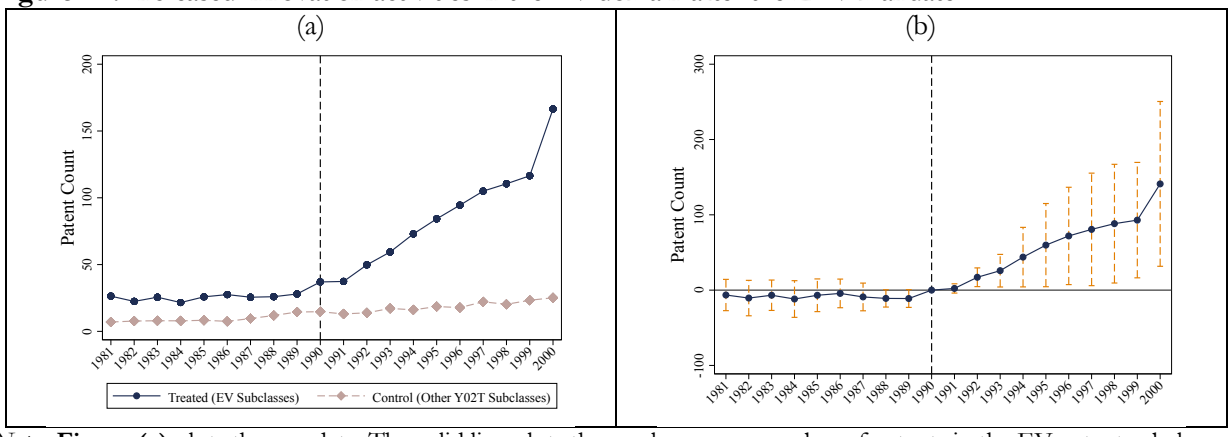
The results in **Table A1** and **Figure A1** suggest that, after the ZEV mandate in 1990, there was an average increase of 70.2 patents (208%) in the EV subclasses, relative to the control subclasses.

Table A1. Increased innovation activities in the EV domain after the ZEV mandate

DV: Patent count	(1)
EV subclass × After ZEV mandate	**70.242****
	(31.363)
R^2	0.254
Observations	665
CPC Subclass FE	Yes
Year FE	Yes

Notes. The data are a panel at the subclass-year level based on patent data for 1981–2000. The treatment group comprises the nineteen patent subclasses directly related to EV technologies, and the control group contains other non-EV subclasses under Y02T. OLS with robust standard errors are clustered at the subclass level. Estimations are presented as coefficient (SE).
*p < 0.10; **p < 0.05; ***p < 0.010.

Figure A1. Increased innovation activities in the EV domain after the ZEV mandate



Notes. **Figure (a)** plots the raw data. The solid line plots the yearly average number of patents in the EV patent subclasses, whereas the dotted line plots the yearly average number of patents in the control patent subclasses. **Figure (b)** plots the difference-in-differences coefficient value. Each point on the graph represents the coefficient value on the covariate *EV subclass*×*Year* and thus describes the relative difference in patent count between EV and control patent subclasses in that year. The bars surrounding each point represent the 95% confidence interval. All values are relative to the base year of 1990.

Table A2. Heterogeneity of main effects by firm size and age, split sample analysis

DV: Share of Inventor Outflow	(1) Subsample: Firm inventor count below median (1986–1990)	(2) Subsample: Firm inventor count above median (1986–1990)	(3) Subsample: Firm age in 1990 less than 8 years	(4) Subsample: Firm age in 1990 more than 8 years
Affected firm × After ZEV mandate	**0.022*** **	**0.002**	**0.014** **	**0.007**
	(0.008)	**(0.004)**	**(0.006)**	**(0.005)**
R^2	0.002	0.006	0.015	0.000
Observations	44,194	47,673	33,267	58,600
Age control	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Notes. The data are a panel at the firm-year level based on patent data for 1981–2000. Different columns correspond to different subsamples. All models are OLS with robust standard errors clustered at the firm level. Estimations presented as coefficient (SE).
*p < 0.10; **p < 0.05; ***p < 0.01.

Note for Figure A2: I provide direct evidence that affected firms' decline in innovation is due to their loss of inventors to EV firms. Specifically, I show that the main results are driven by a subset of affected firms that originally employed inventors with expertise relevant to EV technologies (Figure A2.1), rather than by firms that did not hire these inventors (Figure A2.3); these inventors were subject to increased demand by EV firms after the ZEV mandate and, thus, on average, were more likely to be hired away. Results in Figure A2.1 and Figure A2.2 remain strongly robust to other cutoff number of inventors, such as two, three, five or ten inventors in the top quartile or top 50th percentile

Figure A2. Main results driven by affected firms that hired inventors with expertise close to EV technologies
Figure A2.1. Affected firms restricted to those that hired at least one inventor with expertise very close to EV technology (i.e., proximity in the top quartile) during 1986–1990.

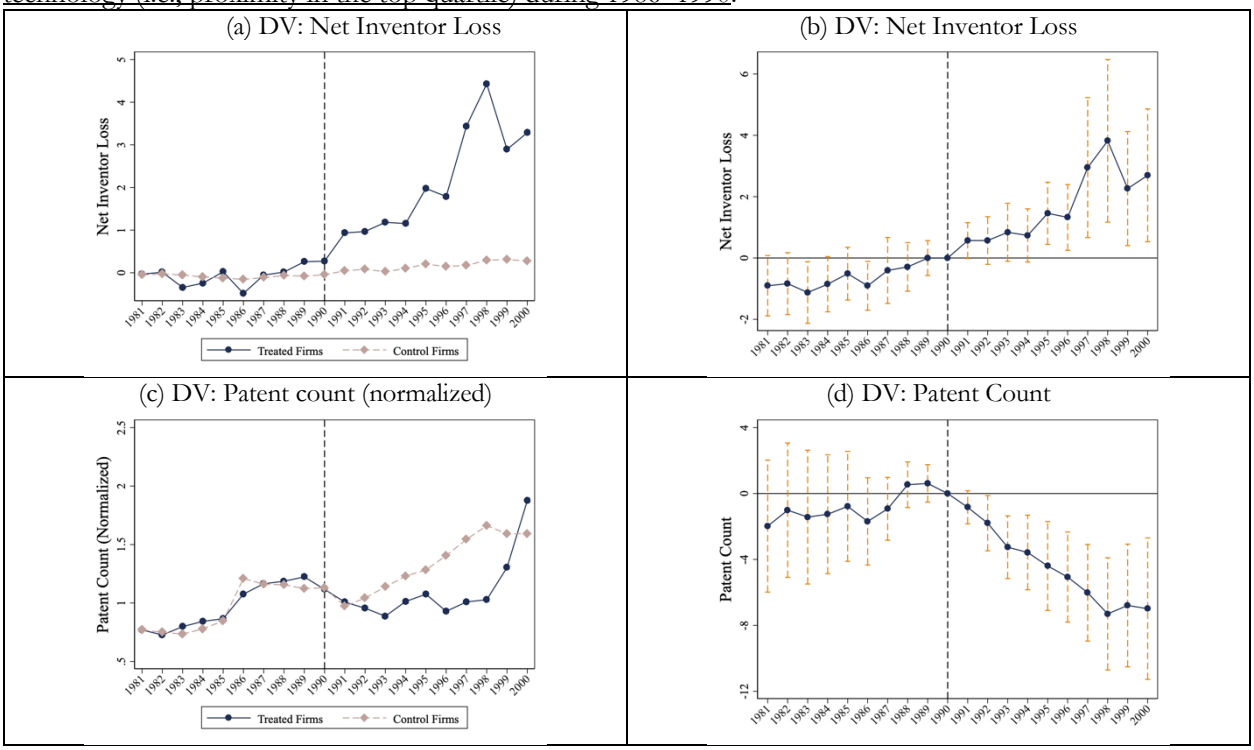


Figure A2.2. Affected firms restricted to those that hired at least one inventor with expertise relevant to EV technologies (i.e., proximity above the top 50th percentile) during 1986–1990

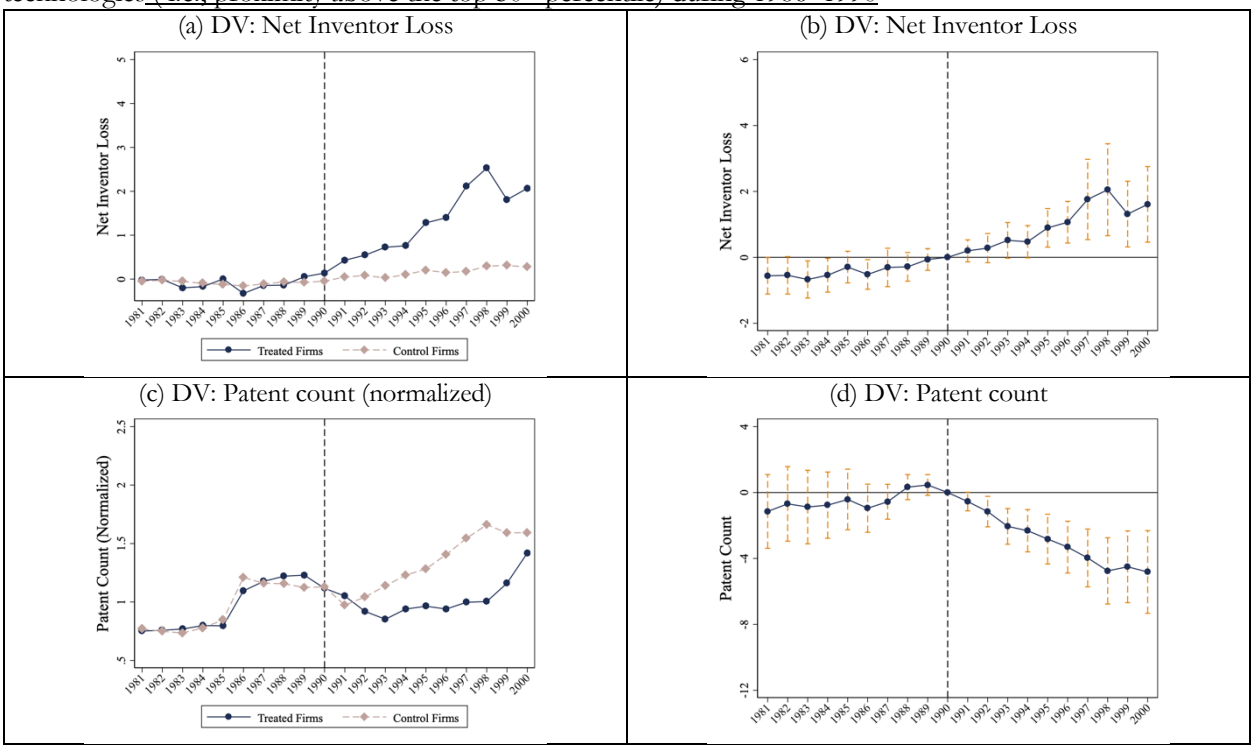
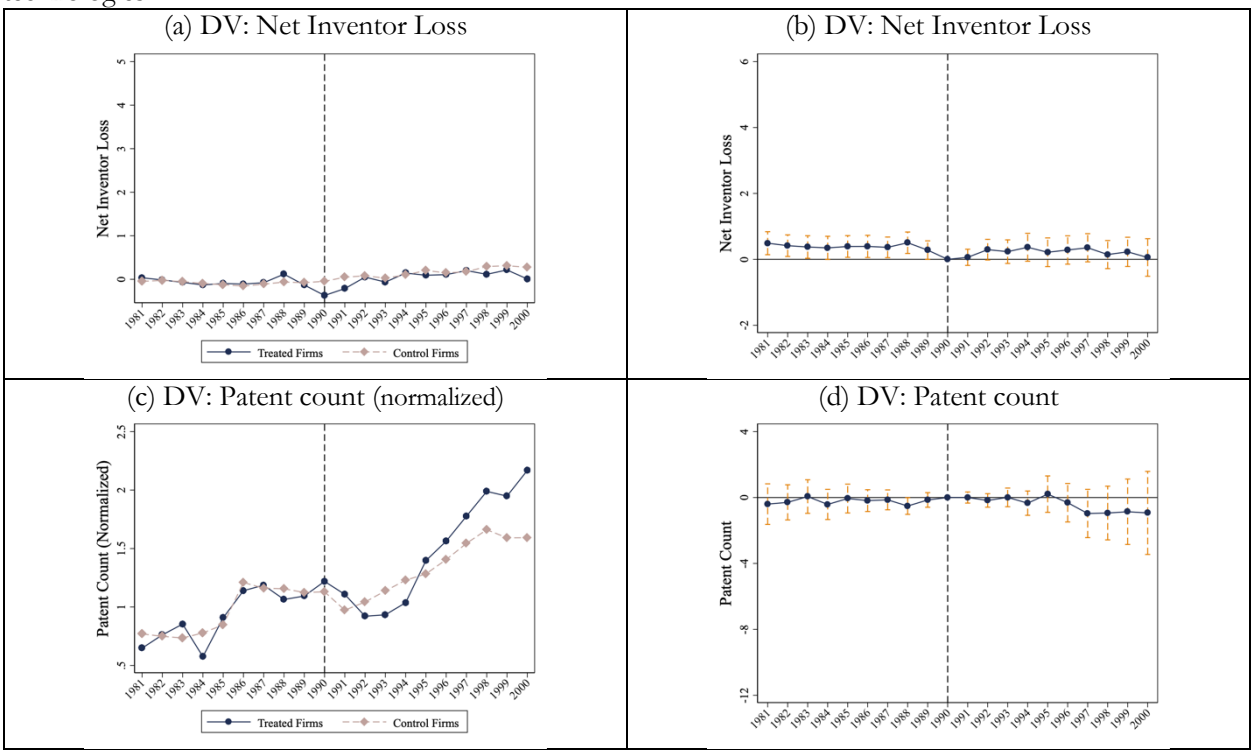


Figure A2.3. Affected firms restricted to those whose inventor expertise during 1986–1990 was far from EV technologies



Note for Figure A3 and Table A3: In my main sample, some firms had zero patents during the early 1990s following the ZEV mandate. While these firms' lack of patents may have been due to their loss of inventors, there is a concern that the main results might be driven solely by these firms. As a robustness check, I repeated the main analysis with a subsample of firms with at least three patents during 1991–1995. The results, presented in Figure A3 and Table A3, remain robust, with even stronger effect sizes.

Figure A3. Main results remain robust when restricting firms to those with at least three patents during 1991–1995.

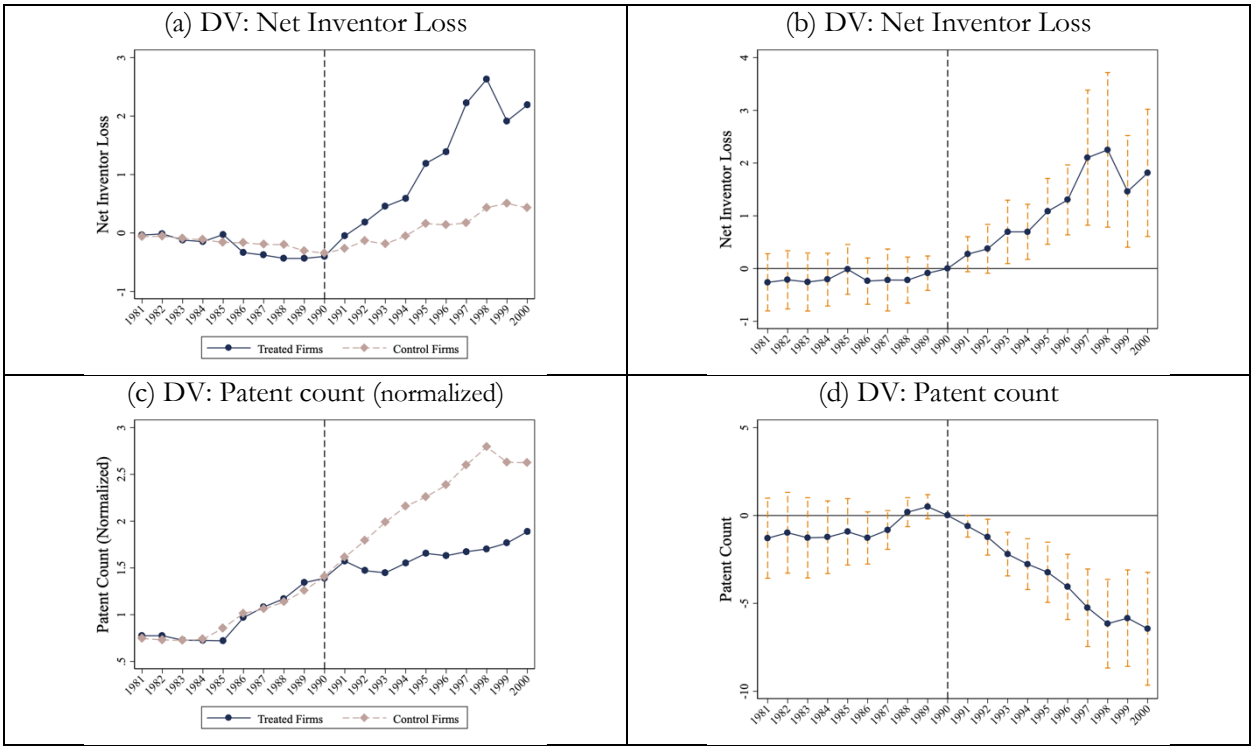


Table A3. Affected firms, restricted to firms with at least three patents after the ZEV mandate (1991-1995), experienced a greater loss of inventors after the ZEV mandate and became less innovative after the ZEV mandate.

	(1) DV: Net inventor loss	(2) DV: Patent count
Affected firm × After ZEV mandate	**1.368***** **(0.320)**	**-3.167***** **(0.896)**
R^2	0.012	0.007
Observations	52,408	52,408
Age control	Yes	Yes
Firm FE	Yes	Yes
Year FE	Yes	Yes

Notes. This table repeats the main results in **Table 3** and **Table 4** but restricts the firms to those with at least three patents within five years after the ZEV mandate (1991–1995). Different columns correspond to different definitions of dependent variables. All models are OLS with robust standard errors clustered at the firm level. Estimations presented as coefficient (SE).
*p < 0.10; **p < 0.05; ***p < 0.01.

Note for Figure A4: In the main analyses, I define affected firms as those with more than 10% of their patents in the adjacent patent subclasses within the five years prior to the ZEV mandate (i.e., 1986–1990). I chose a 10% threshold to ensure that these firms were sufficiently "exposed" to the EV demand shock. In Figure A4, I show that the results remain robust to other cutoffs, such as 7.5% (Figure A4.1), 12.5% (Figure A4.2), 15% (Figure A4.3), and 20% (Figure A4.4).

Figure A4 Main results remain robust to alternative cutoff definitions of affected firms.

Figure A4.1. Affected firms are defined as those with at least 7.5% of patents in adjacent subclasses (1986–1990).

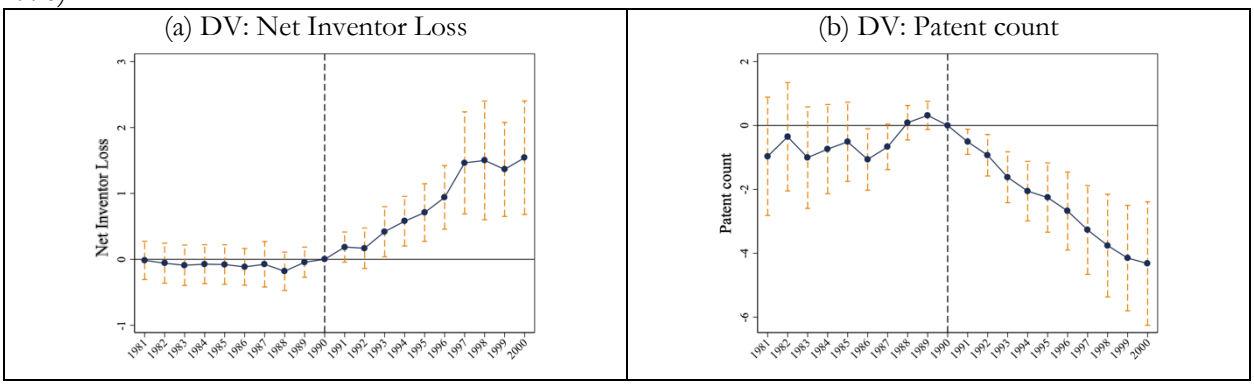


Figure A4.2. Affected firms are defined as those with at least 12.5% of patents in adjacent subclasses (1986–1990).

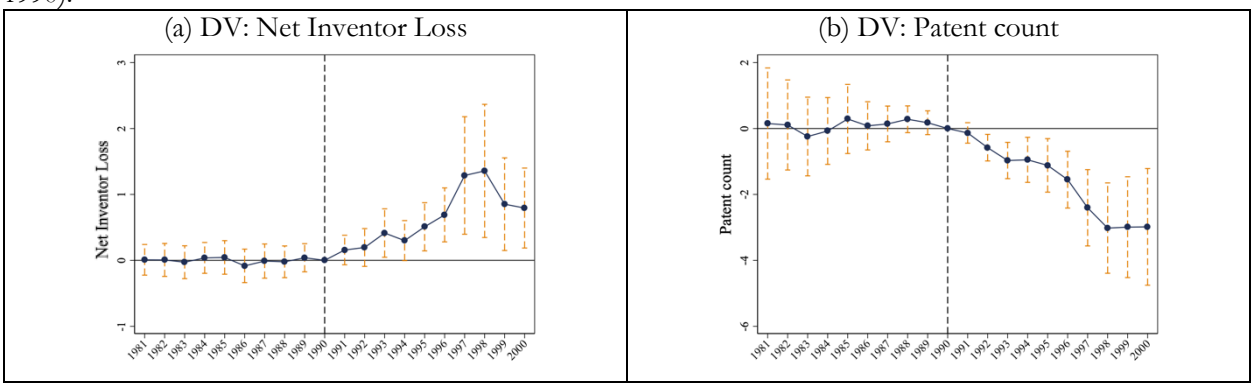


Figure A4.3. Affected firms are defined as those with at least 15% of patents in adjacent subclasses (1986–1990).

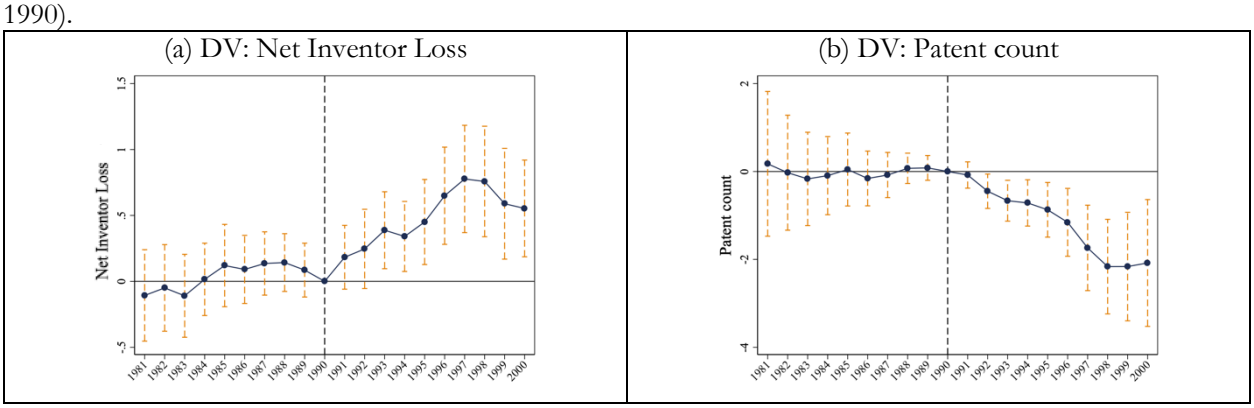
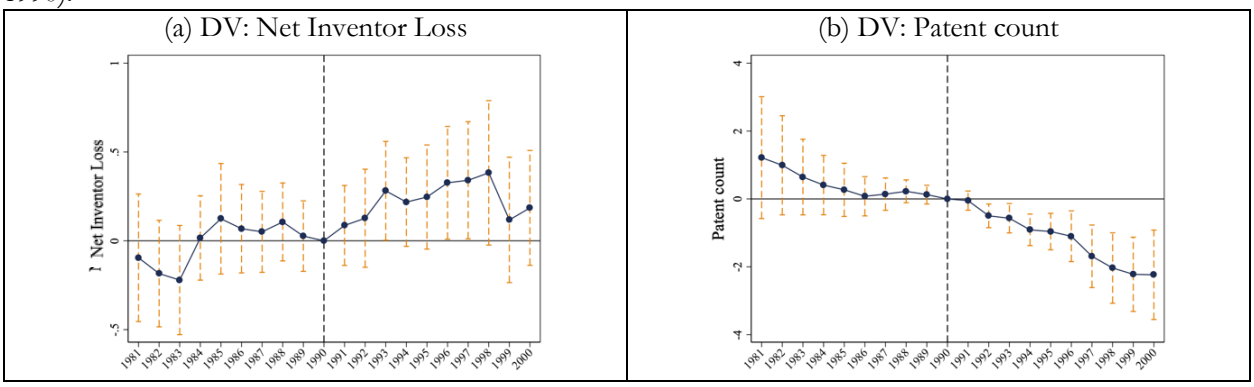


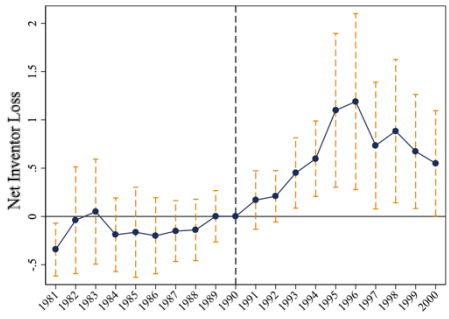
Figure A4.4. Affected firms are defined as those with at least 20% of patents in adjacent subclasses (1986–1990).



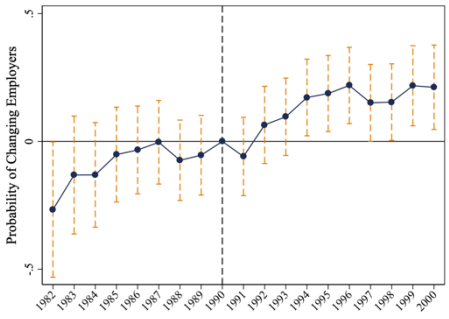
Note for Figure A5: In the main analysis, I define the move-out year as the year when the inventor-employee applied for their first patent at a subsequent firm. I test whether the main results are sensitive to alternative definitions of move-out years, and test two, three, and five years before the year when the inventor-employee applied for their first patent at the subsequent firm. Results at the firm level are presented in Figure A5(a), (c), and e) and results at the individual inventor level in Figure A5(b), (d), and (f), which remain consistent with the main results.

Figure A5. Results reported in Figure 3 are robust to alternative definitions of move-out years (t-2, t-3, or t-5).

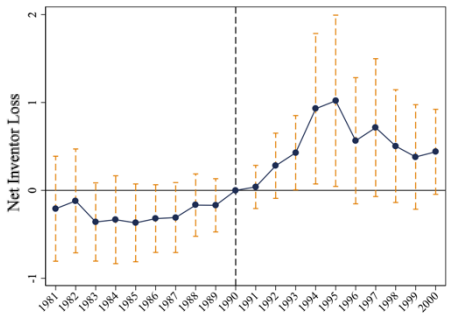
(a) Move-out year defined as **2 years** before the application year of next patent with a different assignee (firm level.)



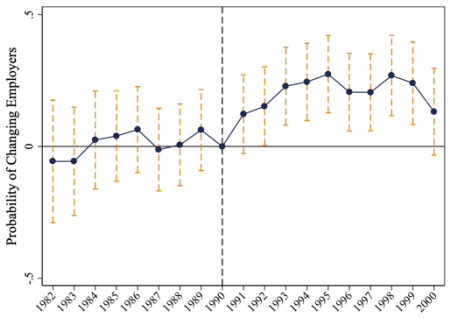
(b) Move-out year defined as **2 years** before the application year of next patent with a different assignee (inventor level).



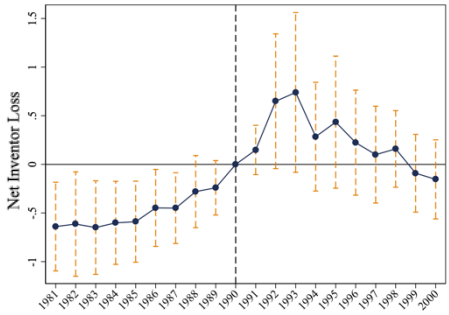
(c) Move-out year defined as **3 years** before the application year of next patent with a different assignee (firm level).



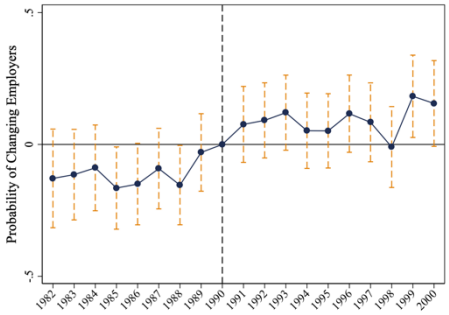
(d) Move-out year defined as **3 years** before the application year of next patent with a different assignee (inventor level).



(e) Move-out year defined as **5 years** before the application year of next patent with a different assignee (firm level).

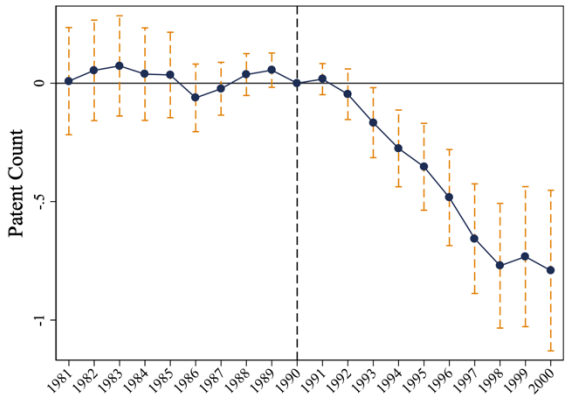


(f) Move-out year defined as **5 years** before the application year of next patent with a different assignee (inventor level).



Note for Figure A6: In the main analysis, I use an OLS model. In Figure A6, I show that the results are robust when using a Poisson model, which may be more appropriate since the dependent variable—patent count—is a count variable.

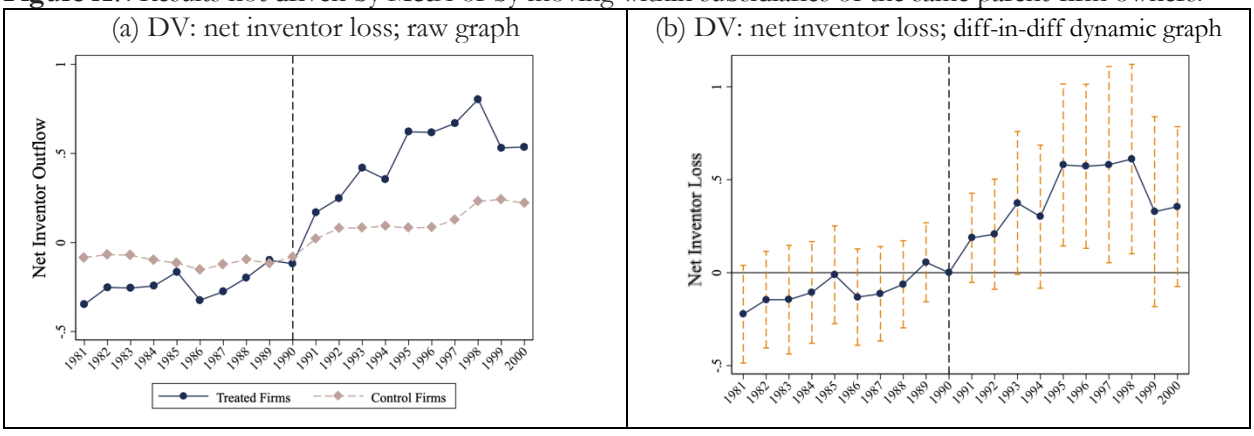
Figure A6. Figure 2 (Affected firms became less innovative after the ZEV mandate) robust to Poisson model.



Notes. The figure repeats the analysis reported in **Figure 2** but runs a Poisson model instead of OLS model.

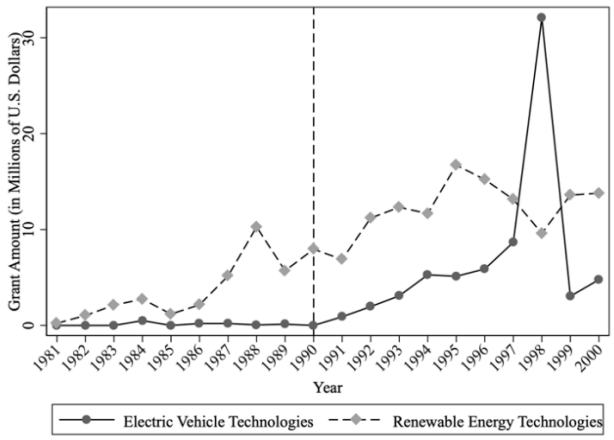
Note for Figure A7: I demonstrate that the main results are not fully explained by alternative explanations, such as movement to subsidiaries or mergers and acquisitions (M&A). To examine whether the main results can be fully explained by movement to other subsidiary firms, I repeat the main analysis in Table 3 but consider only the loss of inventors to incumbent firms. This conservative measure of inventor loss allows me to exclude situations where firms "intentionally" reallocated their inventors to newly founded subsidiaries after the ZEV mandate. Table A4 Column (2) presents the results of this test, which are consistent with the main results. Furthermore, there may be concerns that the main results are driven entirely by M&As among incumbent firms. To address this, I use the DISCERN database developed by Arora, Belenzon, and Sheer (2021), which matches USPTO assignee firms to publicly traded American firms in the Compustat database and traces assignees to their ultimate parent-firm owners. Using this database, I reconstruct my dependent variable of inventor loss to exclude cases where an inventor's subsequent employer belongs to the same ultimate parent firm as the previous employer. The results, presented in Appendix Figure A7, remain consistent with the main findings.

Figure A7. Results not driven by M&A or by moving within subsidiaries of the same parent-firm owners.



Note for Figure A8: One might be concerned that the main finding—that affected firms became less innovative—is driven by the relocation of public funding from (firms in) adjacent domains to (firms in) the EV domain. However, I provide evidence that this mechanism alone cannot fully explain the main results. First, I collected funding data from the Dimensions database, which tracks changes in research funding in different domains over time. I identified funding related to electric vehicle technologies and summed the yearly total grant dollar values. For comparison, I also identified funding related to renewable energy technologies. The data, plotted in Figure A8, show an increase in public funding for electric vehicle technologies following the adoption of the ZEV mandate. At the same time, public funding for renewable energy technologies has steadily increased since the early 1980s, and it did not decrease after the ZEV mandate. I interpret this as evidence suggesting that the decline in innovation among affected firms was not fully driven by a reallocation of public funding from other domains to firms in the EV domain. Furthermore, in Section 6.1 of the main manuscript, I provide direct evidence that the affected firms became less innovative after the ZEV mandate due to losing inventors to EV firms. The main results are driven particularly by affected firms that originally employed more inventors with expertise relevant to EV technologies, rather than by firms that did not hire these inventors.

Figure A8. Public funding in EV and other domains



Note for Table A4: I examine the extent to which affected firms' loss of inventors is driven by loss to incumbent firms or startups. In Table A4, I separate the dependent variable, inventor loss, into losses to incumbent firms and to startups founded after 1990. The results suggest that more than 55% of the inventor loss are driven by loss to incumbent firms, and 40% are driven by loss to new startups.

Table A4. Affected firms' Inventor Loss to Incumbents vs. New Startups.

	(1) DV: Net inventor loss	(2) DV: Net inventor loss to incumbent firms	(3) DV: Net inventor loss to new startups
Affected firm × After ZEV mandate	**0.872***** **(0.204)**	**0.490***** **(0.153)**	**0.342***** **(0.096)**
R^2	0.008	0.001	0.005
Observations	91,867	91,867	91,867
Age control	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes

Notes. The data are a panel at the firm-year level based on patent data for 1981–2000. All models are OLS with robust standard errors clustered at the firm level. Estimations presented as coefficient (SE). *p < 0.10; **p < 0.05; ***p < 0.01.

Note for Tables A5 and A6: Tables A5 and A6 provide additional supporting evidence for the main results presented in Table 5, which show that affected firms in growing technological domains were more likely to lose inventors to EV firms than were other affected firms. In Table A5, I show that affected firms in growing domains and renewable energy domains tended to have originally hired more inventors with expertise relevant to EV technologies, likely because these domains are intellectually closer to the EV technological domains. Indeed, in Table A6, I show that inventors were more likely to be technologically proximate to the EV domain if they had patents in renewable energy domains or if their employers (before 1990) were in growing technological domains.

Table A5. Affected firms in growing domains and renewable energy domains were more likely to have hired inventors with expertise close to EV technologies.

DV: Number of inventors with expertise close to EV tech during 1986-1990	(1)	(2)
Affected firm × Firm in growing technological domains	**4.605*** (0.284)**	
Affected firm × Firm in renewable energy domains		**15.585*** (0.949)**
R^2	0.207	0.234
Observations	5,134	5,134
Age control	Yes	Yes

Notes. The data are a **cross-section at the firm level**. Different columns correspond to different definitions of dependent variables. All models are OLS. Estimations presented as coefficient (SE).
*p < 0.10; **p < 0.05; ***p < 0.01.

Table A6. Inventors in renewable energy domains were more likely to be technologically proximate to the EV domain.

DV: Inventor's technological proximity to the EV domain	(1)	(2)
Inventor's employer in a growing technological domain	**0.119*** (0.008)**	
Inventor had patented in renewable energy domains		**0.042*** (0.004)**
Controls	Yes	Yes
LL	-7079.767	-7145.498
Observations	41,005	41,005

Notes. The data are a **cross-section at the inventor level**. OLS model with estimations presented as coefficient (SE).
*p < 0.10; **p < 0.05; ***p < 0.01.

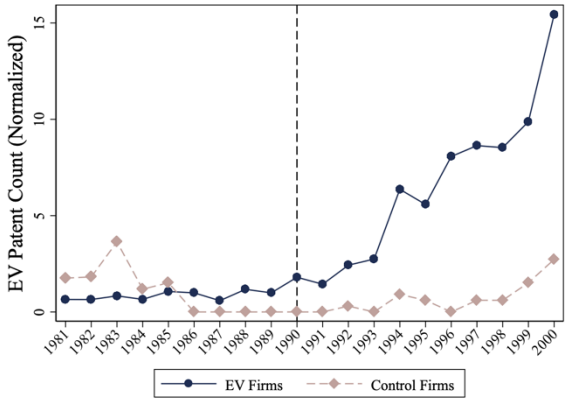
Note for Table A7: Table A7 provides additional supporting evidence for the main results presented in Table 8, which show that after the growth in demand for EV innovations, inventors with expertise relevant to EV technologies were more likely to move from affected firms to EV firms. Moreover, Table A7 further demonstrates that the increased inventor mobility was driven by inventors who moved to EV firms after 1990 (Column [2]), and not by inventors who were already in the EV domain (Column [4]). In fact, if an inventor was already working on EV innovations for an EV employer before 1990, that inventor was less likely to change employers after the ZEV mandate (Column [5]).

Table A7. Inventor Level Analysis: Increased inventor mobility after the ZEV mandate driven by inventors moving from affected firms to EV firms

DV=1 if changed employer in a year	(1) All inventors	(2) Subsample: Inventor who moved to EV firms after 1990	(3) Subsample: Inventor who did not move to EV firms after 1990	(4) Subsample: EV inventors	(5) Subsample: EV inventors who were already employed by EV firms before 1990
EV adjacency × After ZEV mandate	**0.255*** (0.048)**	**0.144** (0.065)**	**0.072 (0.070)**	**-0.504** (0.250)**	**-0.770* (0.456)**
LL/R^2	-80,861.498	-36,634.901	-43,010.858	-5788.062	-1591.085
Observations	420,765	139,782	280,983	26,533	7,073
Controls	Yes	Yes	Yes	Yes	Yes
Inventor FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes

Notes. The data are a panel at the **inventor-year level** based on patent data for 1981–2000. *EV adjacency* is a continuous treatment variable that captures an inventor's technological proximity to the EV domain. It is calculated as the cosine similarity measure between the CPC patent class distribution of an inventor's patents and the CPC patent class distribution of the EV patents. I calculate this measure using patents from 1986–1990 (five years before the ZEV mandate). Different columns correspond to different subsamples. All models are logit regression. Estimations presented as coefficient (SE).
*p < 0.10; **p < 0.05; ***p < 0.01.

Figure A9. Replication of Figure 1(a) with EV patent counts normalized to pre-ZEV mandate levels.



Notes. This figure plots the raw EV patent count, normalized to their pre-ZEV mandate levels. The solid line plots the yearly average normalized number of EV patents by the affected firms, whereas the dotted line plots the yearly average normalized number of EV patents by the control firms.

Appendix B. Additional Details

Appendix B1. List of policy reports on the ZEV mandate used to identify EV Firms.

Anderman M, Kalhammer F, MacArthur D (2000) *Advanced Batteries for Electric Vehicles: An Assessment of Performance, Cost, and Availability*. Prepared for State of California Air Resources Board by The Year, pp.60–65.

California Air Resources Board (2000) *Staff Report: 2000 Zero Emission Vehicle Program Biennial Program Review* (California Air Resources Board, Sacramento, CA).

California Air Resources Board (1998) *Staff Report: 1998 Zero Emission Vehicle Program Biennial Program Review* (California Air Resources Board, Sacramento, CA).

Dixon LS, Porche I, Kulick J (2002) *Driving Emissions to Zero: Are the Benefits of California's Zero Emission Vehicle Program Worth the Costs?* (Rand, Santa Monica, CA).

Kalhammer FR, Kopf BM, Swan DH, Roan VP, Walsh MP (2007) *Status and Prospects for Zero Emissions Vehicle Technology: Report of the ARB Independent Expert Panel*, *1*(1), 12–36.

National Research Council (1998) *Effectiveness of the United States Advanced Battery Consortium as a Government-Industry Partnership*. National Academies Press, Washington, DC).

Turrentine T, Kurani KS (2000) *Progress in Electric Vehicle Technology and Electric Vehicles from 1990 to 2000: The Role of California's Zero Emission Vehicle Production Requirement* (Institute of Transportation Studies, University of California, Davis) Research Report UCD-ITS-RR-00-20.

Woods T (1995) *Zero-Emission Vehicle Technology Assessment. Final Report* (No. NYSERDA-95-11) (New York State Energy Research and Development Authority, New York, NY. Booz, Allen and Hamilton, Inc., McLean, VA).

Table B1. EV Domain: List of EV Patent Subclasses

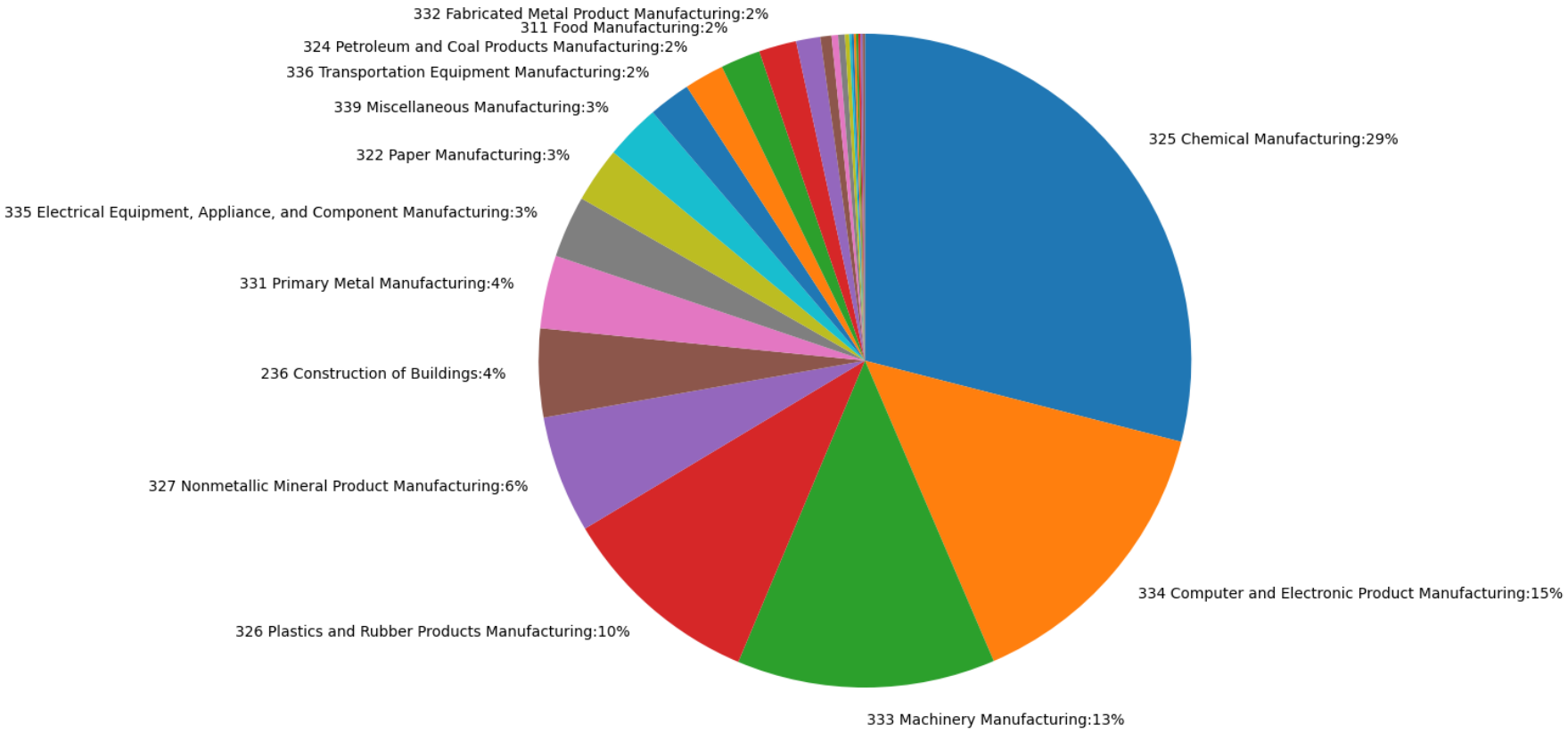
CPC Subgroup id	CPC Subgroup title
Y02T10/60	Road transport of goods or passengers-Other road transportation technologies with climate change mitigation effect
Y02T10/62	Road transport of goods or passengers-Other road transportation technologies with climate change mitigation effect-Hybrid vehicles
Y02T10/64	Road transport of goods or passengers-Other road transportation technologies with climate change mitigation effect-Electric machine technologies in electromobility
Y02T10/642	Road transport of goods or passengers-Other road transportation technologies with climate change mitigation effect-Control strategies of electric machines for automotive applications
Y02T10/70	Road transport of goods or passengers-Other road transportation technologies with climate change mitigation effect-Energy storage systems for electromobility
Y02T10/7044	Road transport of goods or passengers-Other road transportation technologies with climate change mitigation effect-Controlling the battery or capacitor state of charge
Y02T10/705	Road transport of goods or passengers-Other road transportation technologies with climate change mitigation effect- Controlling vehicles with one battery or one capacitor only
Y02T10/7072	Road transport of goods or passengers-Other road transportation technologies with climate change mitigation effect-Electromobility specific charging systems or methods for batteries, ultracapacitors, supercapacitors or double-layer capacitors
Y02T10/72	Road transport of goods or passengers-Other road transportation technologies with climate change mitigation effect-Electric energy management in electromobility
Y02T10/82	Road transport of goods or passengers-Technologies aiming to reduce greenhouse gasses emissions common to all road transportation technologies-Elements for improving aerodynamics
Y02T10/84	Road transport of goods or passengers-Technologies aiming to reduce greenhouse gasses emissions common to all road transportation technologies-Data processing systems or methods, management, administration
Y02T10/86	Road transport of goods or passengers-Technologies aiming to reduce greenhouse gasses emissions common to all road transportation technologies-Optimisation of rolling resistance, e.g. weight reduction
Y02T10/88	Road transport of goods or passengers-Technologies aiming to reduce greenhouse gasses emissions common to all road transportation technologies-Optimized components or subsystems, e.g. lighting, actively controlled glasses
Y02T10/90	Road transport of goods or passengers-Technologies aiming to reduce greenhouse gasses emissions common to all road transportation technologies-Energy harvesting concepts as power supply for auxiliaries' energy consumption, e.g. photovoltaic sunroof
Y02T10/92	Road transport of goods or passengers-Technologies aiming to reduce greenhouse gasses emissions common to all road transportation technologies-Energy efficient charging or discharging systems for batteries, ultracapacitors, supercapacitors or double-layer capacitors specially adapted for vehicles
Y02T90/00	Enabling technologies or technologies with a potential or indirect contribution to GHG emissions mitigation
Y02E60/10	Enabling technologies; Technologies with a potential or indirect contribution to GHG emissions mitigation-Energy storage using batteries
Y02E60/13	Enabling technologies; Technologies with a potential or indirect contribution to GHG emissions mitigation-Energy storage using capacitors
Y02E60/50	Enabling technologies; Technologies with a potential or indirect contribution to GHG emissions mitigation-Hydrogen technology-Fuel cells

Table B2. Representative List of Patent Subclasses for Technological Domains Adjacent to the EV Domain

CPC Subgroup id	CPC Subgroup title
B01D53/326	Separation of gases or vapours; Recovering vapours of volatile solvents from gases; Chemical or biological purification of waste gases, e.g. engine exhaust gases, smoke, fumes, flue gases, aerosols, -by electrical effects other than those provided for in group B01D61/00-in electrochemical cells
B01D71/024	Semi-permeable membranes for separation processes or apparatus characterised by the material; Manufacturing processes specially adapted therefor-Inorganic material-Oxides
B01J8/067	Chemical or physical processes in general, conducted in the presence of fluids and solid particles; Apparatus for such processes-with stationary particles, e.g. in fixed beds-in tube reactors; the solid particles being arranged in tubes-Heating or cooling the reactor
B22D11/0685	Continuous casting of metals, i.e. casting in indefinite lengths -into moulds with travelling walls, e.g. with rolls, plates, belts, caterpillars-Accessories therefor-for cooling the cast product during its passage through the mould surfaces
B22F9/023	Making metallic powder or suspensions thereof-using physical processes-Hydrogen absorption
B29C48/21	Extrusion moulding, i.e. expressing the moulding material through a die or nozzle which imparts the desired form; Apparatus therefor -Articles comprising two or more components, e.g. co-extruded layers-the components being layers-the layers being joined at their surfaces
B29C65/305	Joining ; or sealing; of preformed parts ; , e.g. welding of plastics materials; Apparatus therefor -by heating, with or without pressure-using heated tools-characterised by the means for heating the tool -Electrical means -involving the use of cartridge heaters
B31D1/021	Multiple-step processes for making flat articles; Making flat articles-the articles being labels or tags-Making adhesive labels having a multilayered structure, e.g. provided on carrier webs
B32B38/12	Ancillary operations in connection with laminating processes-Deep-drawing
B60C1/0016	Tyres characterised by the chemical composition or the physical arrangement or mixture of the composition-Compositions of the tread
B60K6/12	Arrangement or mounting of plural diverse prime-movers for mutual or common propulsion, e.g. hybrid propulsion systems comprising electric motors and internal combustion engines; Control systems therefor, i.e. systems controlling two or more prime movers, or controlling one of these prime movers and any of the transmission, drive or drive units
B62D51/002	Motor vehicles characterised by the driver not being seated -characterised by the vehicle control device -comprising safety arrangements
B64C27/001	Rotorcraft; Rotors peculiar thereto -Vibration damping devices
B65G54/02	Non-mechanical conveyors not otherwise provided for-electrostatic, electric, or magnetic
B82Y30/00	Nanotechnology for materials or surface science, e.g. nanocomposites
C01B13/0255	Oxygen; Ozone; Oxides or hydroxides in general-Preparation of oxygen -Purification or separation processes-Physical processing only-by making use of membranes-characterised by the type of membrane
C01B17/20	Sulfur; Compounds thereof-Methods for preparing sulfides or polysulfides, in general
C03C3/087	Glass compositions-containing silica-with 40% to 90% silica, by weight -containing aluminium oxide or an iron compound-containing an oxide of a divalent metal-containing calcium oxide, e.g. common sheet or container glass
C04B35/524	Shaped ceramic products characterised by their composition ; Ceramics compositions ; Processing powders of inorganic compounds preparatory to the manufacturing of ceramic products -based on non-oxide ceramics-based on carbon, e.g. graphite-obtained from polymer precursors, e.g. glass-like carbon material

C08J3/093	Processes of treating or compounding macromolecular substances-Making solutions, dispersions, lattices or gels by other methods than by solution, emulsion or suspension polymerisation techniques-in organic liquids-characterised by the chemical constitution of the organic liquid-Halogenated hydrocarbons
C08J7/043	Chemical treatment or coating of shaped articles made of macromolecular substances -Coating-Improving the adhesiveness of the coatings per se, e.g. forming primers
C08L9/06	Compositions of homopolymers or copolymers of conjugated diene hydrocarbons-Copolymers with styrene
C22C18/00	Alloys based on zinc
C22C21/00	Alloys based on aluminium
C25B11/031	Electrodes; Manufacture thereof not otherwise provided for-characterised by shape or form-perforated or foraminous-Porous electrodes
C25B13/04	Diaphragms; Spacing elements-characterised by the material
D06M15/61	Treating fibres, threads, yarns, fabrics, or fibrous goods made from such materials, with macromolecular compounds; Such treatment combined with mechanical treatment -with synthetic macromolecular compounds -Macromolecular compounds obtained otherwise than by reactions only involving carbon-to-carbon unsaturated bonds-Polyamines
F02B41/10	Engines characterised by special means for improving conversion of heat or pressure energy into mechanical power-Engines with prolonged expansion-in exhaust turbines
F16H63/42	Control outputs ; from the control unit; to change-speed- or reversing-gearings for conveying rotary motion ; or to other devices than the final output mechanism-comprising signals other than signals for actuating the final output mechanisms-Ratio indicator devices
G01R13/403	Arrangements for displaying electric variables or waveforms-using modulation of a light beam otherwise than by mechanical displacement, e.g. by Kerr effect -for continuous analogue, or simulated analogue, display-using passive display devices, e.g. liquid crystal display or Kerr effect display devices
H01G11/74	Hybrid capacitors, i.e. capacitors having different positive and negative electrodes; Electric double-layer [EDL] capacitors [EDLCs]; Processes specially adapted for the manufacture thereof or of parts thereof-Terminals, e.g. extensions of current collectors
H01G9/12	Electrolytic capacitors, rectifiers, detectors, switching devices, light-sensitive or temperature-sensitive devices; Processes of their manufacture-Details-Housing; Encapsulation-Vents or other means allowing expansion
H01L23/49593	Details of semiconductor or other solid state devices -Arrangements for conducting electric current to or from the solid state body in operation, e.g. leads, terminal arrangements ; ; Selection of materials therefor-consisting of soldered ; or bonded; constructions -Lead-frames ; or other flat leads -Battery in combination with a leadframe
H01M10/05	Secondary cells; Manufacture thereof-Accumulators with non-aqueous electrolyte
H01M14/005	Electrochemical current or voltage generators not provided for in groups H01M6/00 - H01M12/00; Manufacture thereof-Photoelectrochemical storage cells
H01M4/60	Electrodes-Electrodes composed of, or comprising, active material-Selection of substances as active materials, active masses, active liquids-of organic compounds
H02J7/022	Circuit arrangements for charging or depolarising batteries or for supplying loads from batteries-for charging batteries from ac mains by converters
H02P5/68	Arrangements specially adapted for regulating or controlling the speed or torque of two or more electric motors -controlling two or more dc dynamo-electric motors
H02P7/281	Arrangements for regulating or controlling the speed or torque of electric DC motors-for regulating or controlling an individual dc dynamo-electric motor by varying field or armature current-by master control with auxiliary power-using discharge tubes or semiconductor devices-using semiconductor devices-the DC motor being operated in four quadrants

Figure B1. Distribution of affected firms by North American Industry Classification System



Notes. As patent data does not include information on the industry of assignee firms, I use the CPC-to-NAICS concordance constructed by Goldschlag, Lybbert and Zolas (2016) to identify the main NAICS industry code for the firms in my sample. Goldschlag, Lybbert and Zolas (2016) use natural language processing to construct vectors of keywords from patents and industry classification descriptions and create a many-to-many probabilistic mapping between USPTO CPC classes and NAICS codes. Using this mapping, I construct a vector of probabilities at the assignee firm-CPC-NAICS level using each firm's patents. Then, I sum this vector of probabilities for all patents at the assignee firm-NAICS level. The resulting probability vector represents each firm's engagement in each three-digit NAICS industry. Lastly, I assign each firm to a main industry based on the highest probability score. This figure plots the distribution of the affected firms' main industry code.

Appendix C. How was the Zero Emission Vehicle (ZEV) mandate adopted?

The ZEV mandate approved by the California Air Resource Board (CARB) is arguably one of the most controversial and daunting technology-forcing policies ever adopted in the United States. The mandate did not arise from concerns over oil, global warming, industry competitiveness, or major technological progress; it resulted mainly due to California's air quality issues and, in particular, to that state's special authority to adopt vehicle emissions standards that were independent from and more stringent than federal standards (National Research Council, 2006). In this appendix, I review how the ZEV mandate was adopted and other related events at the time of adoption.

1. Background and Regulatory Environment Before the ZEV Mandate

In the history of air pollution, California has distinguished itself among other US states as having the worst pollution. During the late 1970s and the 1980s, the pollution issue accelerated further for two primary reasons. First, both the state's population and its Vehicle Miles Traveled (VMT) grew significantly throughout these decades. Specifically, from 1970 through 1995, VMT increased 2.5 times, from 103 billion to 270 billion, and the population increased by 60%, from 20 million to 32 million (Vergis and Mehta, 2012). Along with this growth in population and VMT, the automobile fuel economy had stagnated over the 1980s, chiefly as a result of the increased number of on-road gasoline vehicles and of the growth in market share (more than 27% in 1987) of sport utility vehicles (SUVs) and light trucks, which are about one-third less fuel-efficient than regular passenger cars (Heavenrich, 2006). These factors offset the air-quality improvement brought by emission control technologies (e.g., catalytic converters, variable valve control) and caused significant pollution problems for the state.

As a result, major metropolitan areas in the state, including Los Angeles,[36] suffered the worst air quality in the country. California dominated the list of "top ten areas with highest smog" in the United States; five areas had the highest ground-level ozone levels and eight areas had the most frequent violations of federal standards. For example, in 1987, when California set the state standard for ozone at 0.09 ppm (180 μg/m3) for a 1-hour averaging time, the level in many areas in the state exceeded this state ozone standard by more than a hundred times (South Coast Air Quality Management District, 2003). Furthermore, in 1990, when the ZEV mandate was adopted, gasoline cars accounted for 55% of NO_x and 47% of ROG emissions in the state (CARB, 2005). This worsening air pollution resulted in significant social consequences and monetary losses (Shrank and Lomax, 2002).

At the same time, by the late 1980s regulatory attitudes toward air quality were also changing. In July 1987, in a case brought by the Natural Resources Defense Council, the US Court of Appeals ruled in an 11-to-0 vote that the EPA could use only health factors to determine safe emission levels of toxic pollutants and could not base decisions on the cost to industry or technological feasibility. In the full court, Circuit Judge Robert H. Bork wrote, "[Toxic pollutant safety levels] must be based solely upon the risk to health. The [EPA] administrator cannot under any circumstances consider the cost and technological feasibility at this stage of the analysis" (Lewis, 1987).

The air pollution problem also put California at risk of losing federal funding and support. In 1988, southern California—including the Los Angeles basin—had violated the federal standard for ozone levels significantly for more than 176 days, a number far higher than any other city in the United States (Reinhold, 1989). As a result of its air-quality problem, California risked losing federal funds for constructing transportation infrastructure unless it showed progress toward or an openness to adopting further regulations to improve its air quality (Collantes and Sperling, 2008).

In summary, by the end of the 1980s, the increasingly serious air-quality issue had drawn significant attention from the state government. In parallel with the pollution problem was a growing belief by the government and industry that existing emission control technologies could not solve the problem. As a result,

[36] Los Angeles in particular was severely affected because of its unique location. The county and its suburbs are located in a basin surrounded by mountains to the east and onshore winds from the west easily trap air pollution. Furthermore, strong sunlight in the area led to photochemical reactions that further contributed to smog formation (Calef and Goble, 2007).

the state agency, including the CARB, recognized the urgent need to improve air quality and realized that only more drastic steps could solve the problem. In this context, CARB adopted the ZEV mandate.

2. General Motors' (GM) 1990 Impact Prototype

In January 1990, Roger Smith, then GM's chairman and CEO, publicly demonstrated the Impact prototype: a two-seater electric vehicle (EV) powered by a lead-acid battery with a range of 70 miles. Although it may be tempting to believe that the public introduction of this vehicle revealed major technological progress in EV technologies and led to the adoption of the ZEV mandate, studies suggest that this is less likely to be the case (Calef and Goble 2007; Collantes and Sperling 2008; Vergis and Mehta 2012). In particular, after conducting more than fifty in-depth interviews with key individuals involved in the event and the policy process of the ZEV mandate, Collantes and Sperling (2008) found that, at the time of the public demonstration, corporate leaders—including some inside GM and some from other car companies, such as Ford and Chrysler—thought that Smith was overselling the Impact prototype.[37]

Actually, the conceptualization of regulating zero emission vehicles began years before GM's demonstration (Collantes and Sperling 2008). Don Drachand, then chief of CARB's Motor Vehicle Emissions Control Division, was convinced as early as 1988 during the policy formulation process that existing emission regulation of gasoline vehicles would not be enough to curb the pollution problem, and that regulation of zero emission vehicles seemed the only means to improve air quality. Although the CARB staff understood that the progress in EV and battery technologies at the time was stagnant and that no breakthroughs had occurred over time, they were confident that only with the ZEV mandate development would the industry pursue zero-emission vehicle technologies. Therefore, Drachand proposed regulating zero-emission vehicles.

CARB's staff viewed GM's Impact demonstration as a sign that GM would not present "open opposition" to the adoption of the mandate. If all automakers strongly opposed the mandate initially, it would have been difficult to bring the ZEV proposal to the board. GM's public demonstration of the Impact prototype, albeit with insufficient performance, gave Drachand more confidence to push through the ZEV mandate and provided an example of a vehicle that could meet the standard of what CARB called "zero emission."

In summary, most studies suggest that the auto industry's large-scale R&D efforts toward EV-related technologies in the 1990s were due mainly to the technology-forcing nature of the mandate instead of to competitive pressures driven by GM's Impact EV prototype or ex ante technological advancement in EV technologies (e.g., Brown et al., 1995; Calef and Goble 2007; Collantes and Sperling 2008; McConnell et al., 2012). In addition, the studies agree that the ZEV mandate, which was adopted to address California's severe air-pollution problem in the 1980s, was a relatively extreme policy lacking sufficient feasibility analysis of the market and the technology. Upon interviewing key individuals at leading companies such as Honda and Saft, Calef and Goble (2007) suggested that "the American, French and Japanese automakers that had neglected research on EVs and advanced batteries throughout the 1970s and the 1980s resumed their interest in it mainly as a result of the ZEV mandate." In line with this, Firoz Rasul, the CEO of Ballard Power Systems (a leading firm that invests in fuel cell vehicles), noted in 2001: "It's not just going to happen by market forces ... I can certainly tell that Ballard would not be here today, if it was not for the zero emission vehicle regulation." Similarly, Roberta Nichols, a director at Ford, noted that "without the environmental issues and the (ZEV) regulations in California, we probably wouldn't be moving the electric vehicle technology" (Nadis and MacKenzie 1993). Indeed, in the late 1990s (and especially after the ZEV requirements were dropped in 2003), many firms realized that EV technologies were not ready and increasingly switched their attention to other technologies, such as hybrid and hydrogen technologies, which were, at the time, more feasible than the EV technologies.

[37] Specifically, Collantes and Sperling (2008) suggest that "as some interviewees pointed out, General Motors has a particular public relations style. In an effort to portray itself favorably in the eyes of government and the public, the company often crafts public statements in ways that may lead to misinterpretations. Some audiences may (intentionally or not) be led to believe that the company is farther along a particular technological learning curve than it really is."

3. Reactions to the ZEV Mandate

Unsurprisingly, after the ZEV mandate was adopted, automakers—including GM—strongly opposed it (Calef and Goble 2007). The industry perceived the mandate to be extreme and radical in requiring a new technology and considered EV technologies, especially battery technologies, which were mainly lead-acid at the time, to be far from ready to produce a viable EV.

However, despite their strong opposition to the mandate, auto manufacturers had no choice but to invest in R&D efforts and comply with the mandate. For example, Chrysler, Ford, and GM responded by pulling resources from the government and forming the U.S. Advanced Battery Consortium (USABC), whose primary goal was to improve existing battery technology and develop a viable EV by 1998. As a result, significant research and innovation activities in EV and battery technologies occurred during the 1990s (National Research Council 1998; Burke et al., 2000; Turrentine and Kurani, 2000). In **Appendix Figure A1** and **Figure C1**, I show that innovation indeed increased (as captured by increased patenting activities in EV patent classes) as did research activities in EV technologies (as captured by academic publications in EV research topics[38]) after the ZEV mandate. Importantly, I do not find pre-trends in EV patenting and publication activities before the ZEV mandate, which further supports the notion that there was no major advancement in EV technologies in the 1980s.

However, despite these efforts and progress, CARB reviewed the technological progress in 1996 and determined that the existing lead-acid batteries would not satisfy the EV requirements such as a reasonably long vehicle drive range per vehicle charge, and that other newly invested technologies would not be ready by the late 1990s. As a result, CARB suspended the 2% and 5% requirements for the 1998–2001 model years in return for the automakers' commitment to introduce EVs as early as 1996. Then, in January 2001, CARB again reviewed the progress and further lowered the 2003 sales requirement from 10% to 2%.

In February 2001, realizing that meeting the sales mandate using existing technologies would not be feasible, GM filed a lawsuit in California to overturn the ZEV mandate (O'Dell, 2002). In 2002, GM, DaimlerChrysler, and Isuzu Motors filed a second lawsuit against the ZEV mandate, alleging that it was a poorly disguised effort by the state to usurp the federal government's authority to regulate fuel economy standards. As a result, in 2003, CARB had to drop the sales requirements for any pure zero-emission vehicles.[39,40] The fact that automakers eventually filed a lawsuit against CARB to drop the ZEV mandate further suggests that these firms had expected neither the mandate nor its EV sales requirement that contributed to increased demand for EV technologies during the 1990s.

In summary, the ZEV mandate is well suited for studying how changes in market demand within one technological domain (i.e., the EV domain) affect innovation progress and inventor loss among firms in adjacent domains. As suggested by the qualitative evidence above and **Appendix Figure A1** and **Figure C1**, the ZEV mandate led to an unpredicted and unprecedented increase in demand for EV innovations in the 1990s. Most importantly, it is unlikely that firms in domains adjacent to the EV domain—particularly those adversely affected by the ZEV mandate—would have anticipated, let alone supported, the adoption of the mandate.

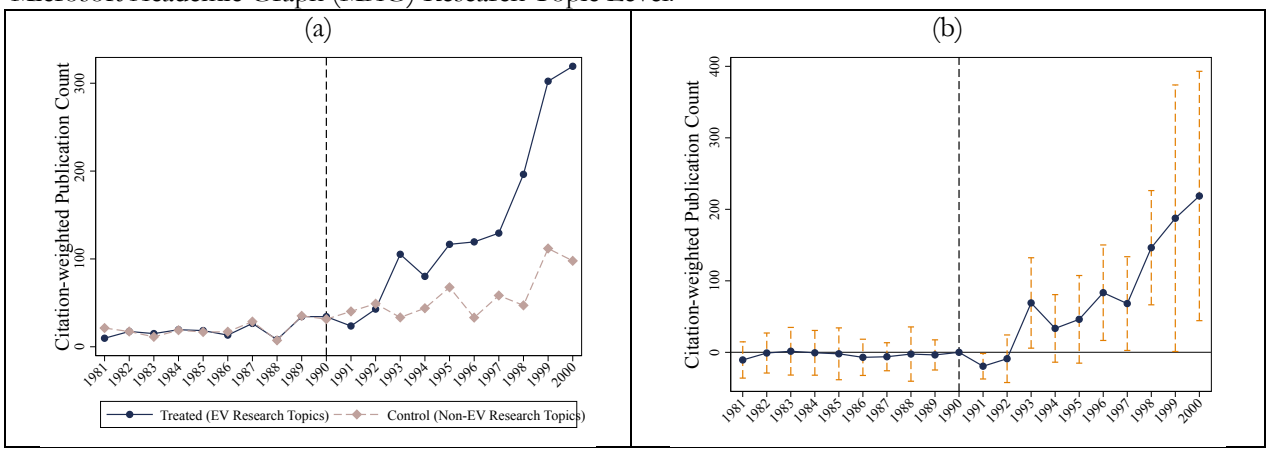
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[38] I collect publication data from Microsoft Academic Graph, which is one of the largest databases for academic publications (Wang et al., 2020; Arora et al., 2024; Yin et al., 2022).

[39] Instead, CARB mandated, by 2005, the sales of partial-allowance zero-emissions vehicles (PZEVs)—gasoline vehicles that meet the Super Ultra Low Emissions Vehicle (SULEV) tailpipe standard and have zero evaporative emissions—and hybrid vehicles.

[40] Since CARB reduced the sales requirement in 2001 and eventually eliminated it altogether in 2003, I choose to focus my sample period on the years 1981–2000. This sample period represents ten years before and ten years after adoption of the ZEV mandate. Specifically, as illustrated in **Appendix Figure A1** and **Figure C1**, there is evidence of increased demand-driven innovation activities in EV technologies from 1991 through 2000.

Figure C1. Effects of the ZEV Mandate on Yearly Citation-Weighted Academic Publications at the Microsoft Academic Graph (MAG) Research Topic Level.



Notes. **Figure (a)** plots the raw data. The solid line plots the yearly average citation-weighted publication count of EV research topics, whereas the dotted line plots the yearly average citation-weighted publication count of the control research topics. **Figure (b)** plots the difference-in-differences coefficient estimates. Each point on the graph represents the coefficient value on the covariate *EVResearchTopic* × Year and thus describes the relative difference in citation-weighted publication count between EV and non-EV research topics in that year. The bars surrounding each point represent the 95% confidence interval. All values are relative to the base year of 1990. The lack of pre-trends in EV publications before the ZEV mandate supports the notion that there was no major advancement in EV technologies in the 1980s.

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